

The New g-2 Experiment at Fermilab

Adam Lyon

(Fermilab/Scientific Computing Division)

Argonne HEP Seminar, January 2012



A short quiz

I remember from my Biology class in the 9th grade...

Which one of the following is not like the others?

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Which one of the following is not like the others?

Electron?

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Proton?

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Proton?

Neutron?

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Electron?

Proton?

Neutron?

Crouton?

A short quiz

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Which one of the following is not like the others?

Electron?

Proton?

Neutron?

Crouton!

A more advanced quiz

Which one of the following is not like the others?

One purpose that muons seem to have is that they are excellent tools for probing fundamental physics, as you will see in this seminar.

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A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

Crouton?

Muon?

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A more advanced quiz

Which one of the following is not like the others?

Electron?

Proton?

Crouton?

Muon????

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A more advanced quiz

Which one of the following is not like the others?



Isidor I. Rabi

Who ordered
that?

?

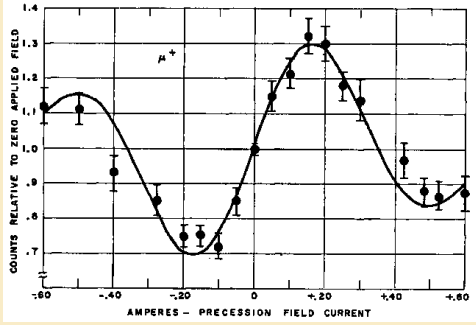
ron?

Muon????

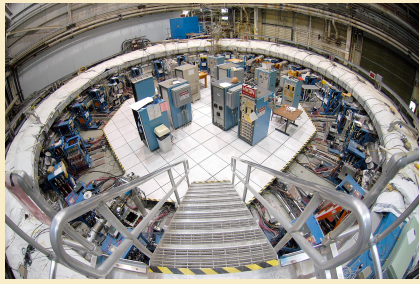
One purpose that muons seem to have is that they are excellent tools for probing fundamental physics, as you will see in this seminar.

Outline of this seminar

1) Introduction to the muon magnetic dipole moment



2) Brief history of the measurement

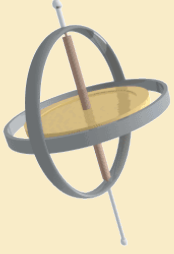


3) Current state of experiment and theory (Brookhaven E821)

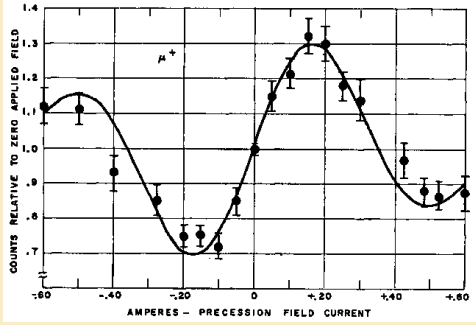


4) The future Fermilab E989 Experiment

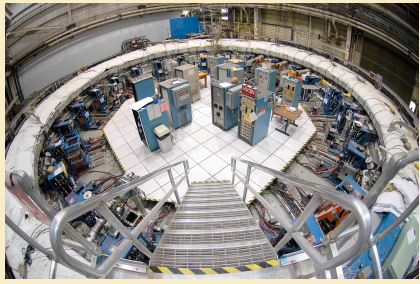
Outline of this seminar



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3) Current state of experiment and theory (Brookhaven E821)



4) The future Fermilab E989 Experiment

The basics of the “g-factor”

Orbiting charged particle: $\vec{\mu}_L = \frac{q}{2m} \vec{L}$

Particle with spin has an *intrinsic* magnetic moment:

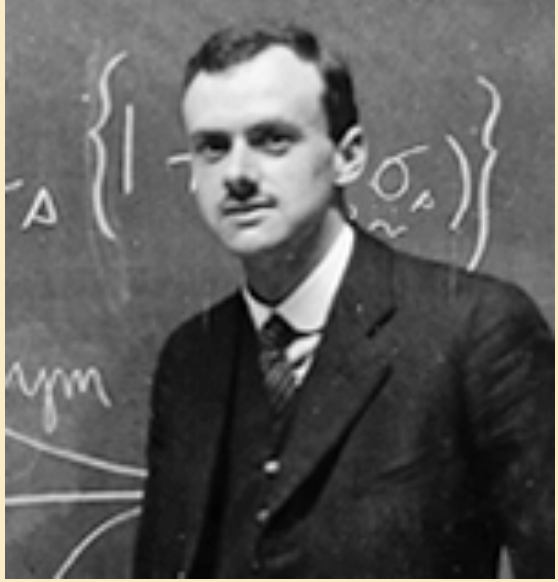
$$\vec{\mu}_S = g \frac{q}{2m} \vec{S}$$

Classical system: $g = 1$

For the electron: $g = 2$ was known from Stern-Gerlach and spectroscopy experiments

Why does $g = 2$?

Predicted theoretically by Dirac in 1928



Paul Dirac

$$\left(\gamma^\nu \left(p_\nu - \frac{e}{c} A_\nu \right) - mc \right) \psi = 0$$

$$i \frac{\partial \psi}{\partial t} = \left[\frac{1}{2m} (\vec{p} - e \vec{A})^2 - \overset{\text{red arrow}}{2} \frac{e}{2m} \vec{S} \cdot \vec{B} \right] \psi$$

**Aside: In 1933, measured for proton $g = 5.6$,
neutron (by measuring deuteron) $g = -3.8$
Protons and Neutrons are not like Electrons!**

For the electron, g remained $= 2$ for twenty years

Why does $g \neq 2$???

But, there's more to this story ...

1948 - Kusch and Foley measure $g_e > 2$ by 0.12% in spectroscopy



Henry Foley



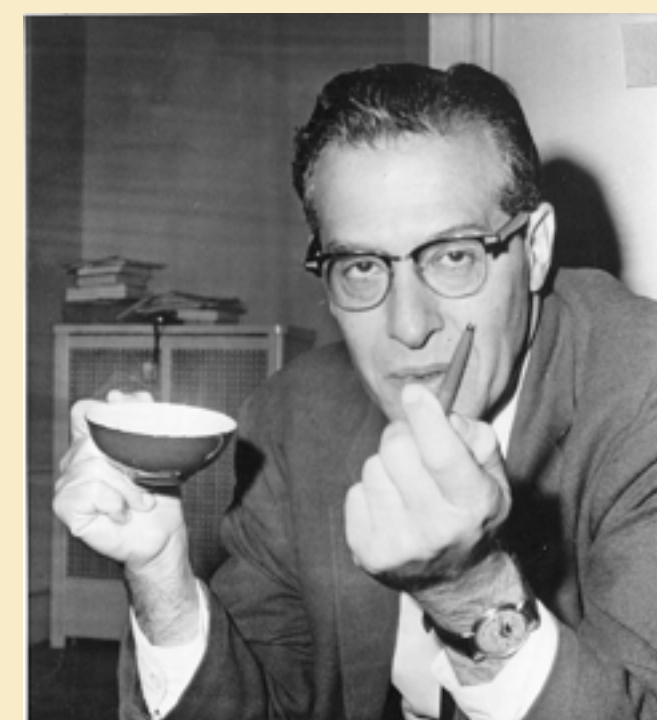
Polykarp Kusch

An anomalous magnetic moment

$$a = \frac{g - 2}{2} \quad a_e = 0.00119(5)$$

Soon after, Schwinger calculates first order QED correction

$$a_e = \alpha/2\pi = 0.00118$$



Julian Schwinger

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tenth of a percent

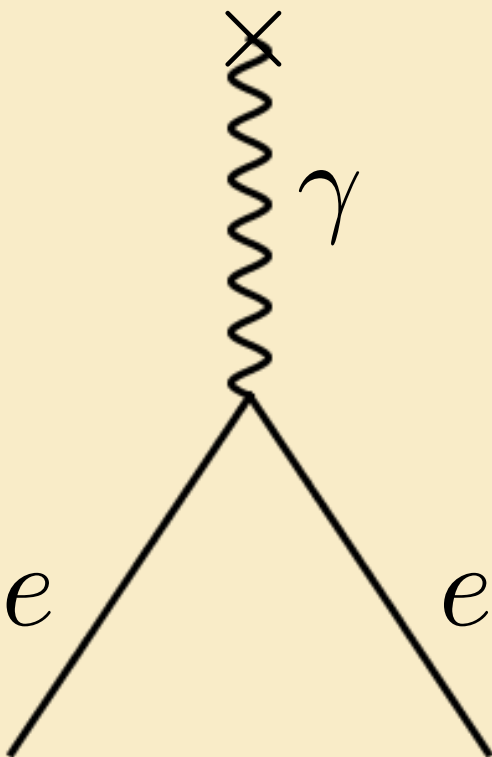
Kusch won the nobel prize along with Lamb

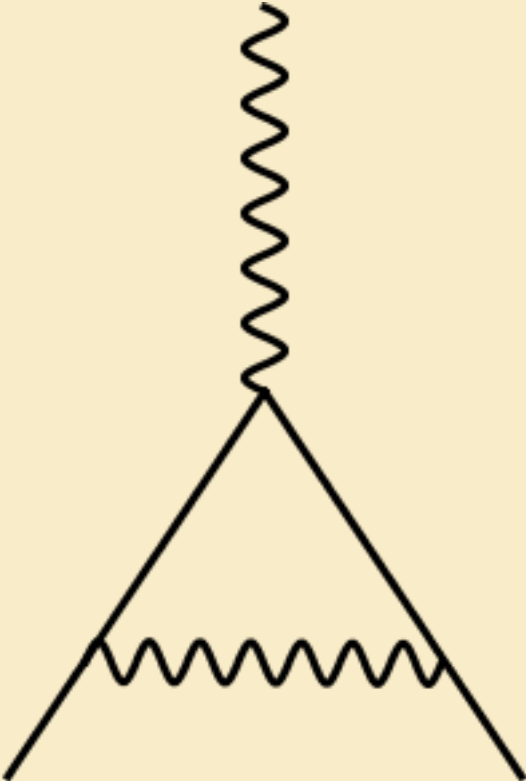
There were hints of an anomalous value in hyperfine splitting of H and D


Schwinger – original caption is “His laboratory is his pen”


A new understanding begins

Empty space is not empty

$g_e =$ 

$+$ 

$+$ 

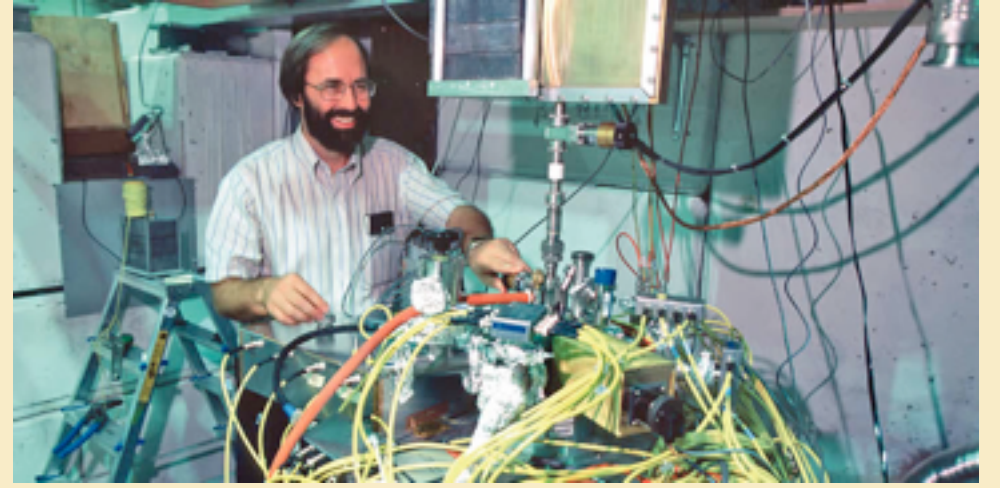
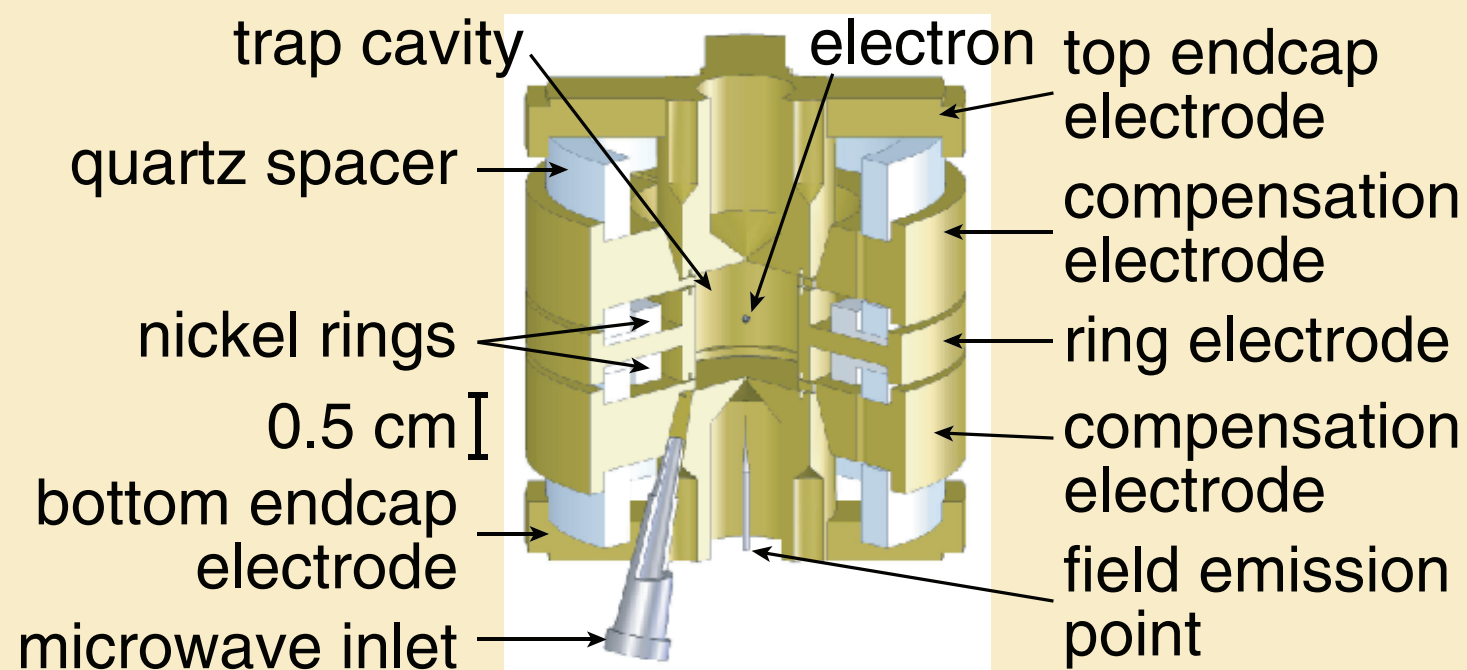
2 $+$ 0.00236 $+$ 

The beginnings of QED and the Standard Model

Currently, a_e is known to sub-ppt

Gabrielse (2006 & 2008):

Previous result was 20 years prior



$$a_e = 0.00115965218073(28)$$

Hanneke et al., PRL100 (2008) 120801

Agrees with SM. So are we done?

Put electrons in a penning trap and leave it in there for several months.

Note that experimental error is smaller than theory error!!

Beyond electrons are muons

Weak and hadronic corrections to a_e are tiny

$1.628(20) \times 10^{-12}$	$0.0297(5) \times 10^{-12}$	See M.Passera INT2008
Weak correction	Hadronic correction	

But for the muon, sensitivity goes as $(m_\mu/m_e)^2 \approx 40,000$

So look at muons!

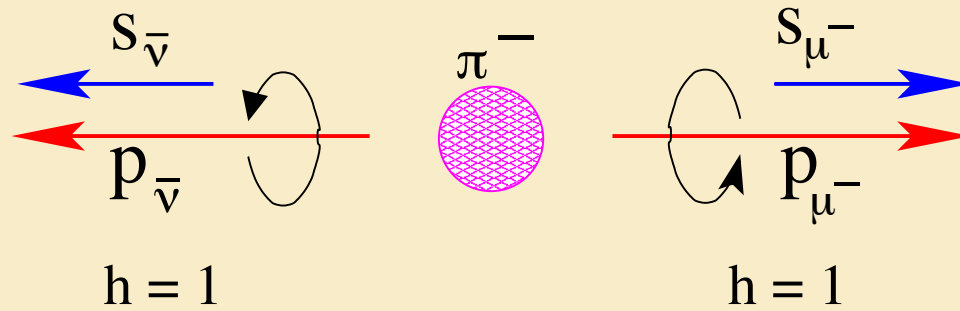
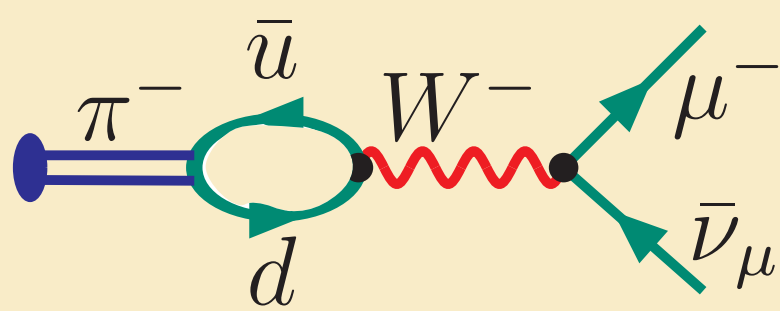
Taus would be even better, but lifetime and production rates are too small to be useful here

Muons are the only particle left for this type of fundamental measurement!

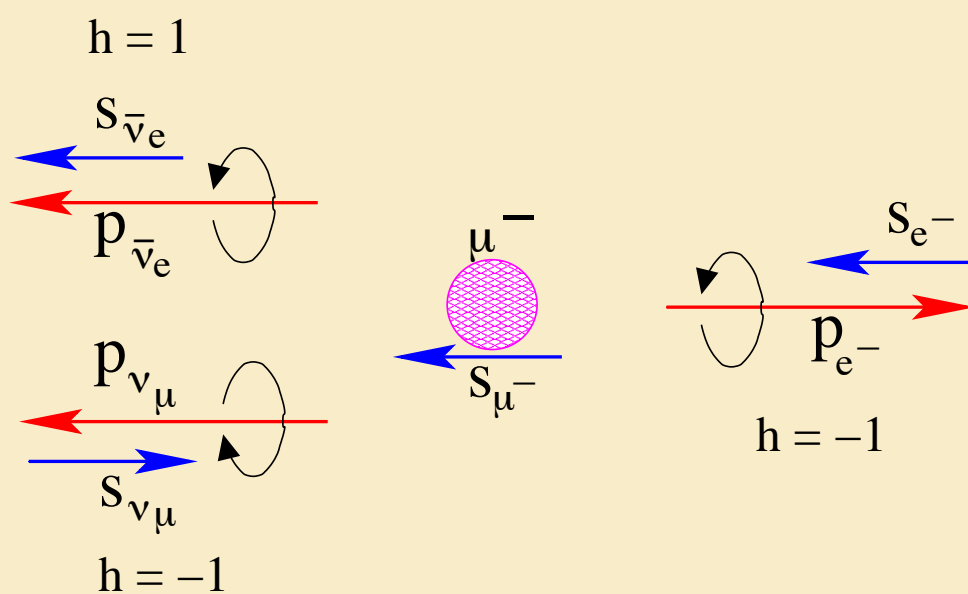
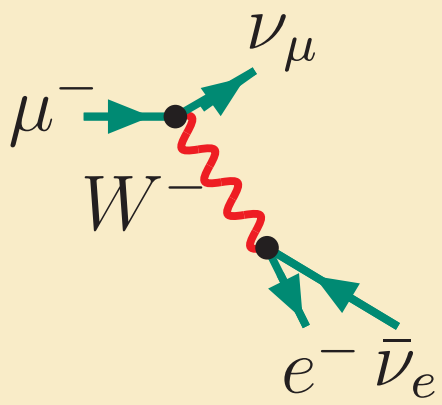
Muons and spin are an ideal match

Some lucky breaks from parity violation:

High momentum muons from pion decays are longitudinally polarized



Muon decays are “self-analyzing”



Highest energy electrons are emitted along (opposite) direction of muon+(-) spin in muon rest frame

Why pions decay to muons and not electrons: In rest frame of pion, the anti-neutrino and electron are back to back. For massless neutrinos, they always have right handed helicity (spin projected onto momentum direction). Since pion is spin zero, the electron must be right handed too. But in the limit of massless electron, the weak decay prefers left handed electrons and muons. Since the muon is more massive, it wins over the electron and muons are produced.

In the CM frame, the μ^- is emitted with spin parallel to momentum. Boosting to lab frame, the highest momentum muons are those emitted in the same direction of the pion, and so there's a correlation between muon momentum and spin direction. Choosing these high momentum muons, you get a longitudinally polarized beam

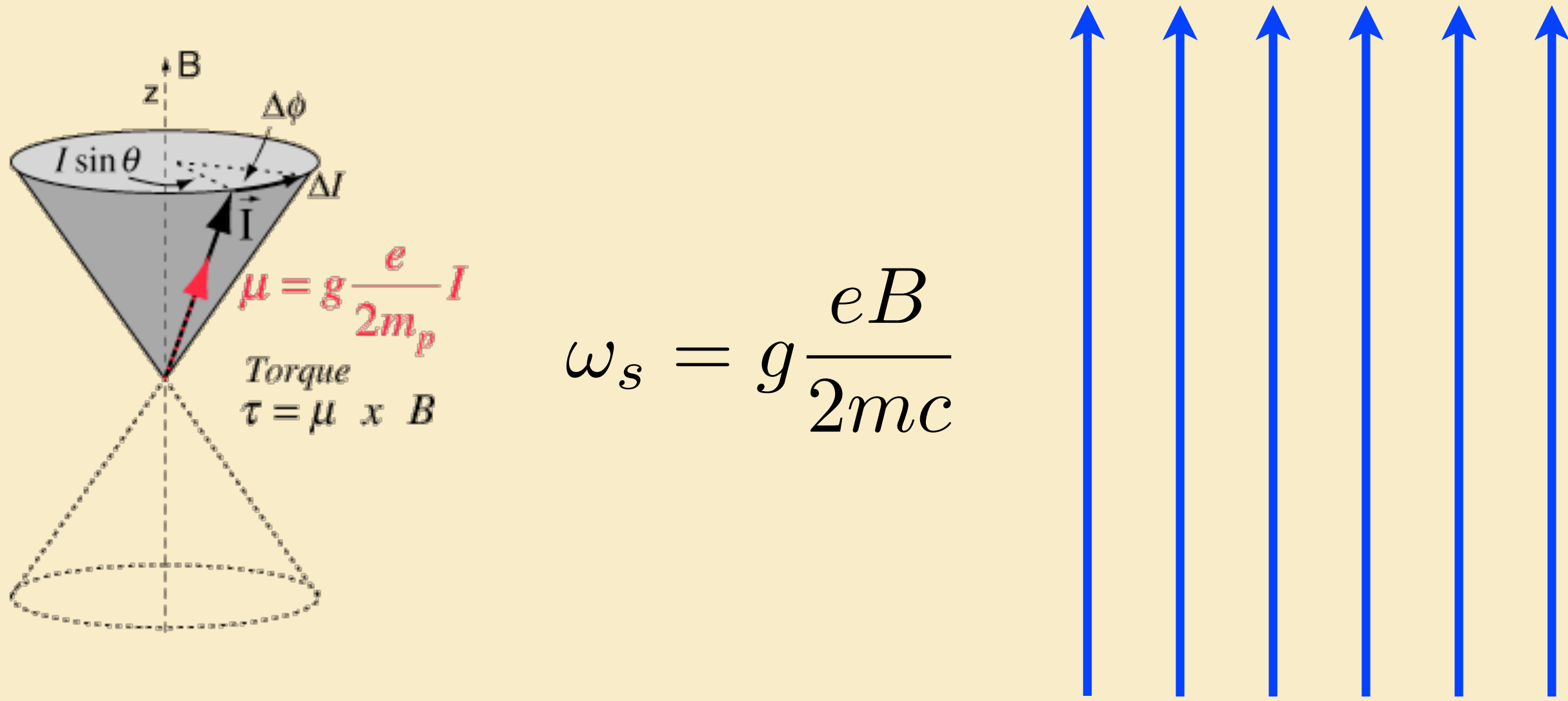
For μ^+ , the situation is reversed, Neutrino is left handed, and so the μ^+ is left handed too. So the μ^+ spin is anti aligned with the momentum

For decay – highest energy electrons are when neutrinos are emitted in the same direction. The the electrons gets half of the muon rest mass ($E_{\max} = 53 \text{ MeV}$) while the other 53 MeV is shared by the neutrinos. Since neutrinos are emitted in the same direction, weak decays say their helicities must be opposite and so their spins are opposite. Since the neutrino spins cancel, the electron must then have the spin of the muon to satisfy conservation of ang mom.

V-A says that weak decays like to couple to left handed electrons, so the high energy electron is emitted with direction OPPOSITE to its spin. So you can find out the spin direction of the muon by looking at the direction high energy electrons are emitted.

How to measure a_μ

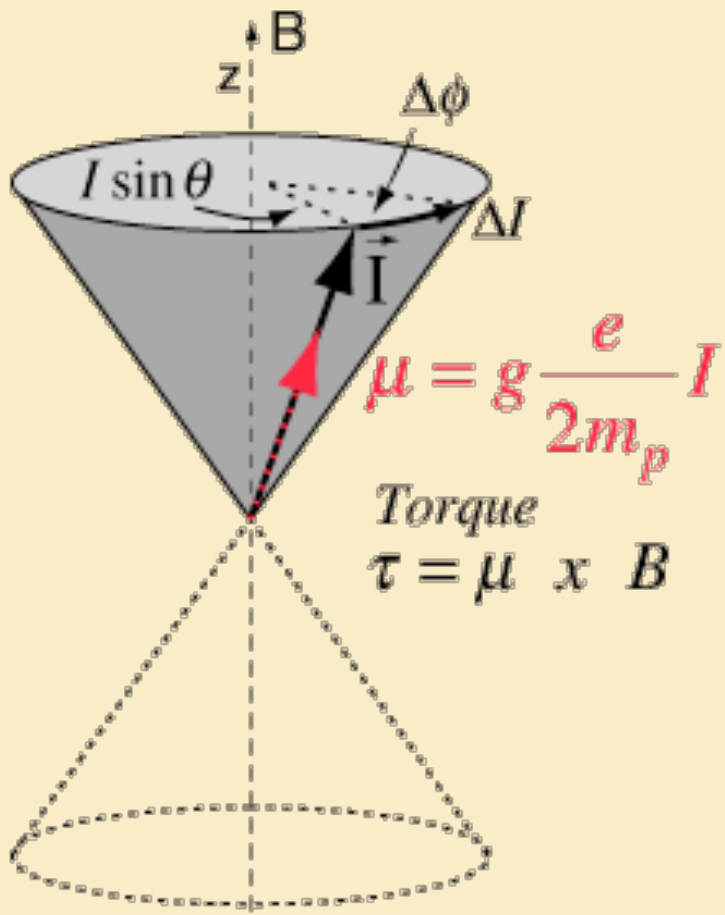
Idea: Put polarized muons in a magnetic field and measure Larmor precession



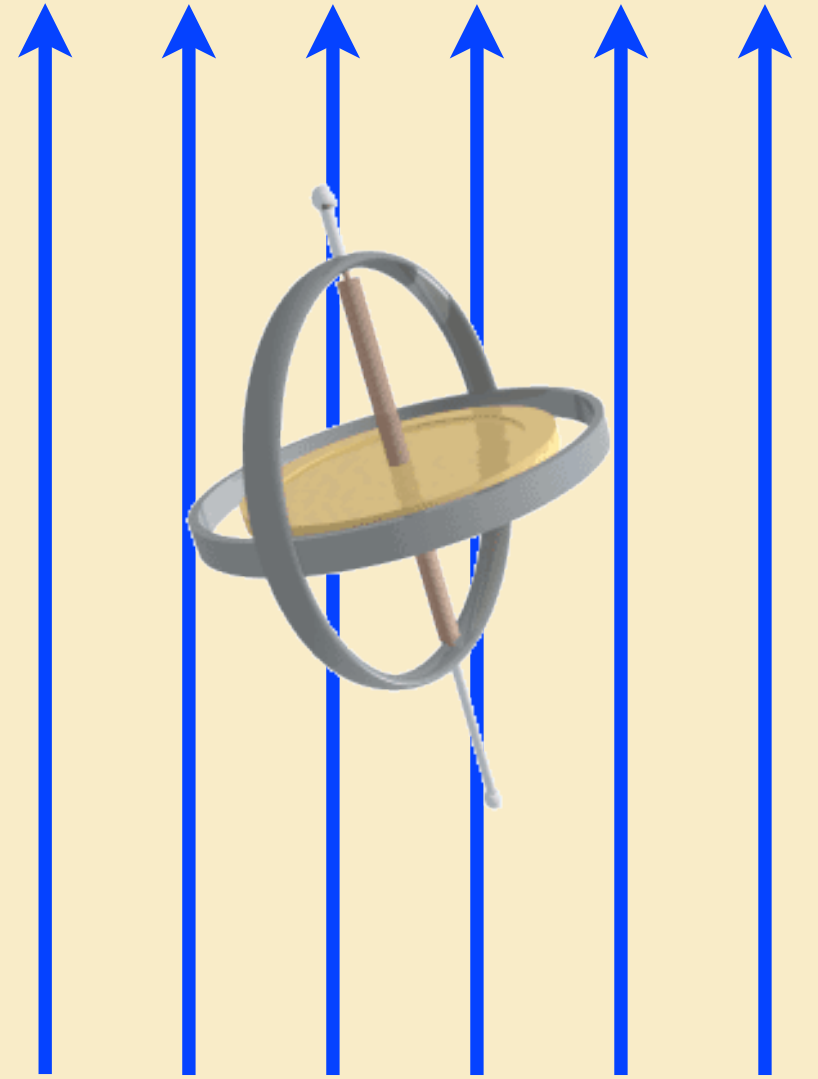
Frequency of this precession is ω_s

How to measure a_μ

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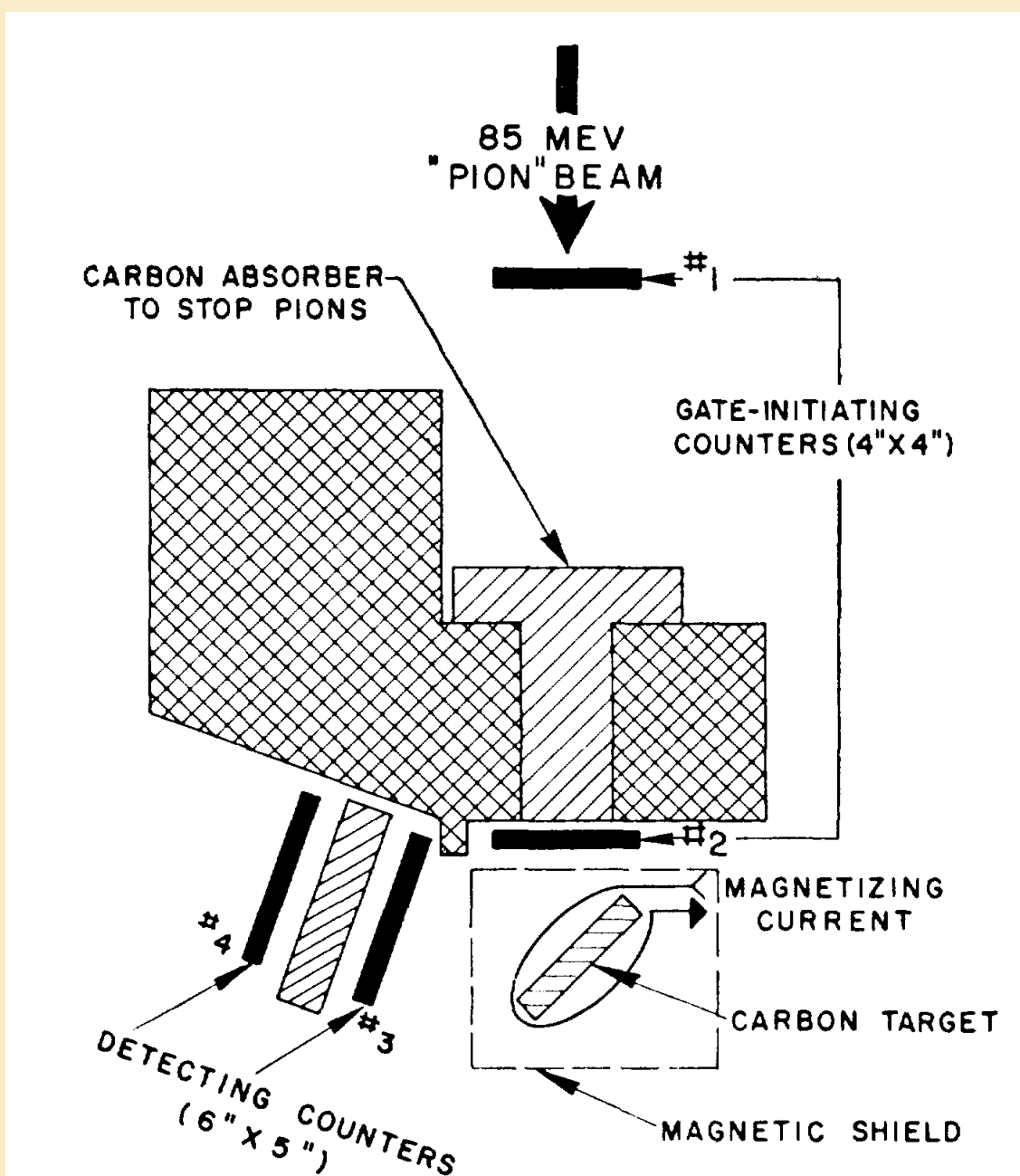
$$\omega_s = g \frac{eB}{2mc}$$



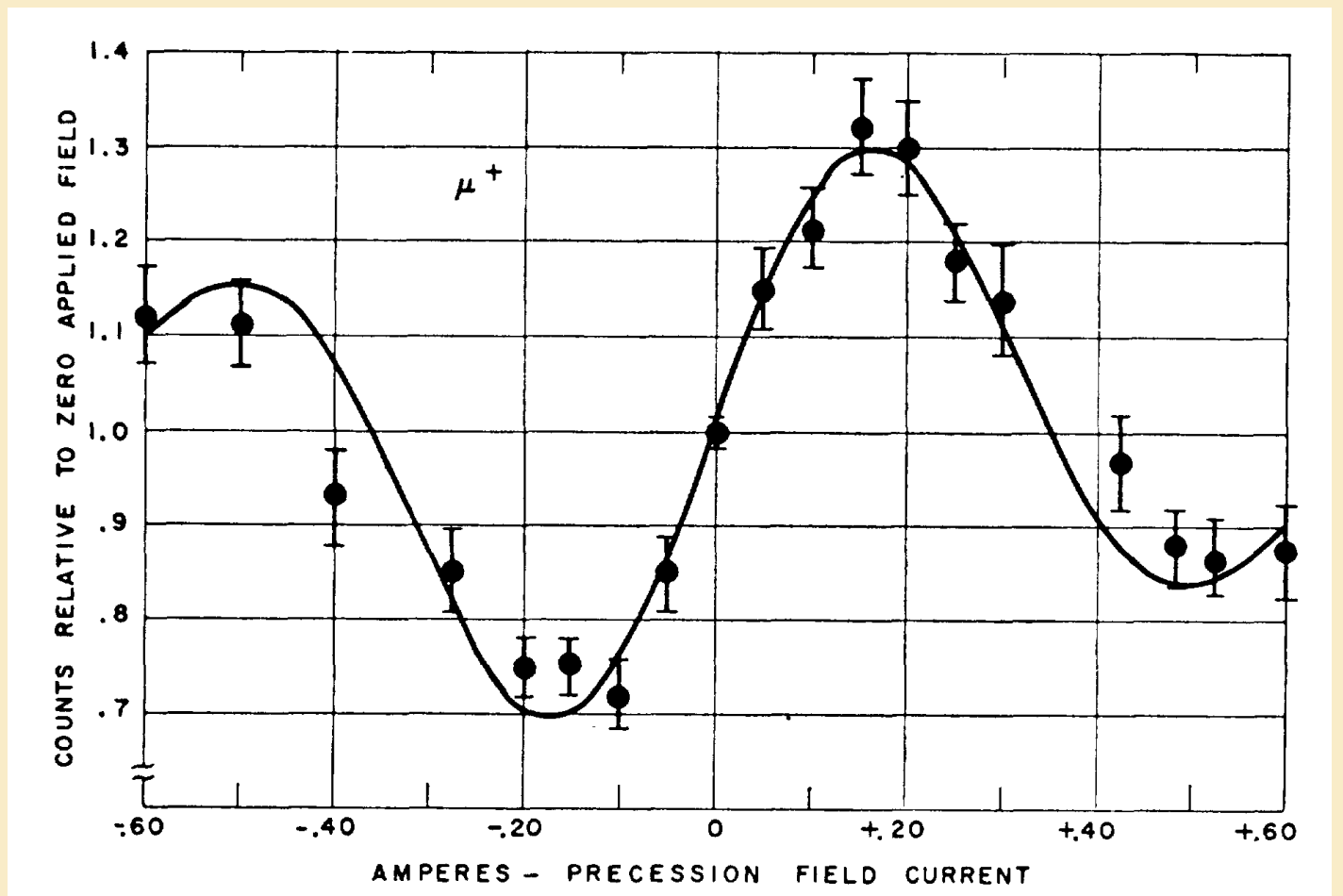
Frequency of this precession is ω_s

The first experiments for a_μ

1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)



Direct measurement of g -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

muons behave like electrons

The first experiments for a_μ

Such experiments continued at Nevis and CERN until 1965

Best measurement CERN I (1965)

$$a_\mu = 0.001\,162(5) \ (\pm 4300 \text{ ppm})$$

Just like the electron!
Sensitive to 2nd order QED

Time for a new idea...



The first CERN g-2 team: Sens, Charpak, Muller, Farley, Zichichi (CERN/1959)

Storage rings enter the picture

Cyclotron frequency for particle in a B field

$$\omega_c = \frac{eB}{mc\gamma}$$

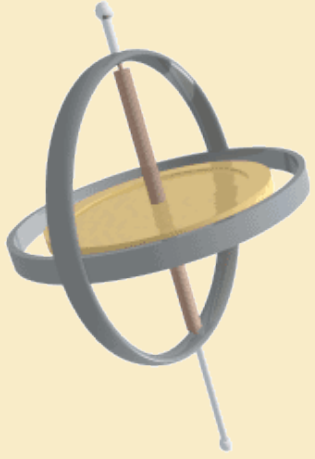
Larmor frequency with Thomas precession

$$\omega_s = \frac{eB}{mc} \left(\frac{1}{\gamma} + a_\mu \right)$$

Storage rings enter the picture

Cyclotron frequency for particle in a B field

$$\omega_c = \frac{eB}{mc\gamma}$$



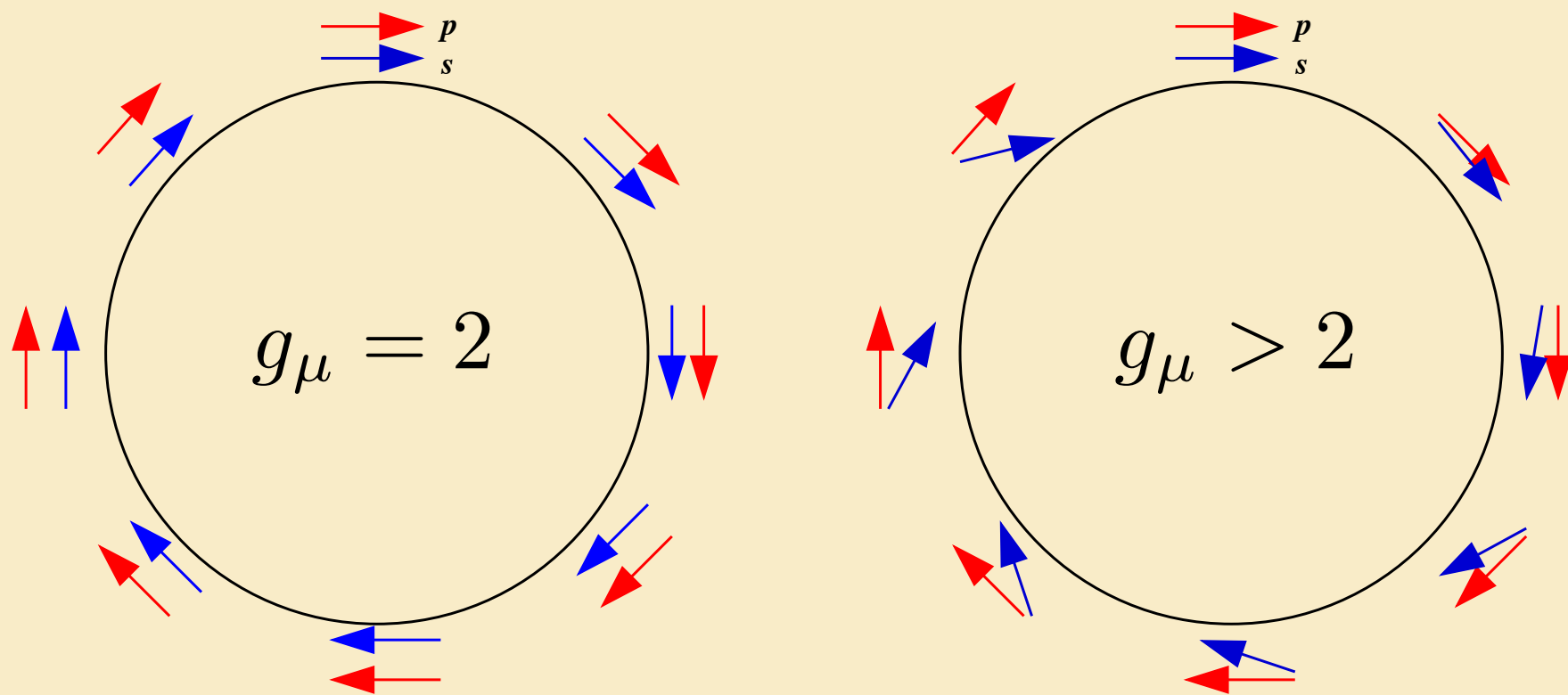
Larmor frequency with Thomas precession

$$\omega_s = \frac{eB}{mc} \left(\frac{1}{\gamma} + a_\mu \right)$$

Difference of frequencies

Another lucky break

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$



Say Omega A

Lock step at $g=2$ – leads if $g > 2$

Picture is not quite accurate – at muon momentum of the BNL experiment, it takes 29 trips around the ring for one cycle of the precession

Improvements for free

Since $a_\mu \approx g_\mu/800$ measuring ω_a gives you x1000 in precision over measuring g

We can avoid the uncertainty in muon mass with,

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}} \quad \mathcal{R} = \omega_a/\omega_p, \quad \lambda = \mu_\mu/\mu_p$$

ω_p is proton Larmor precession (can measure with NMR)

λ is from hyperfine muonium structure (Hughes) 120 ppb

Second CERN experiment results (1968)



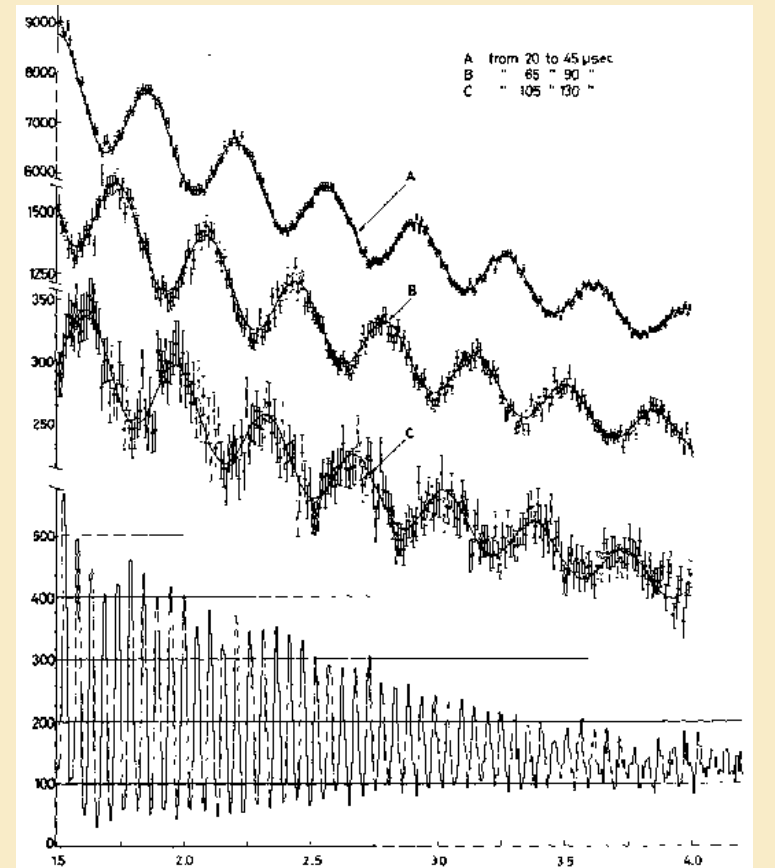
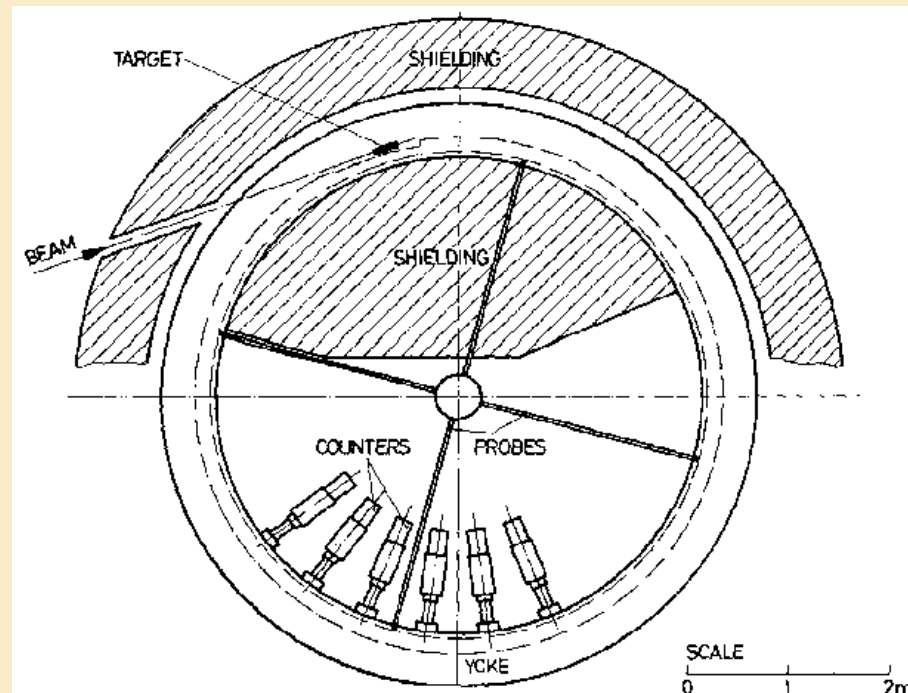
$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + \phi)]$$

Positrons over threshold

$$p_\pi = 1.27 \text{ GeV}/c$$

$$B = 1.7 \text{ T}$$

**Electrons go
inward to detectors**



130 μs of wiggles

$$a_\mu = 0.001\,166\,16(31), \pm 270 \text{ ppm}$$

Sensitive to 3rd order QED and light-by-light scattering

If you have a counter to count positrons above an energy threshold, the number of counts you will see is an oscillating wiggle subject to an overall decrease due to the muon lifetime

Cern II ended with stat err of 2.3×10^{-7} and sys of 1.9×10^{-7}

Bottom part of plot is the rotation frequency. Fourier transform is the radial distribution

At first measurement was 1.7 sigma from theory. Light-By-Light resolved it

A miracle happens here

How to keep the muons vertically confined?

2nd CERN used radial variation in B field (big systematic)

Use electrostatic focusing quadrupoles - but adds complications

$$\vec{\omega}_a = \frac{e}{mc} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) (\vec{\beta} \times \vec{E}) \right]$$

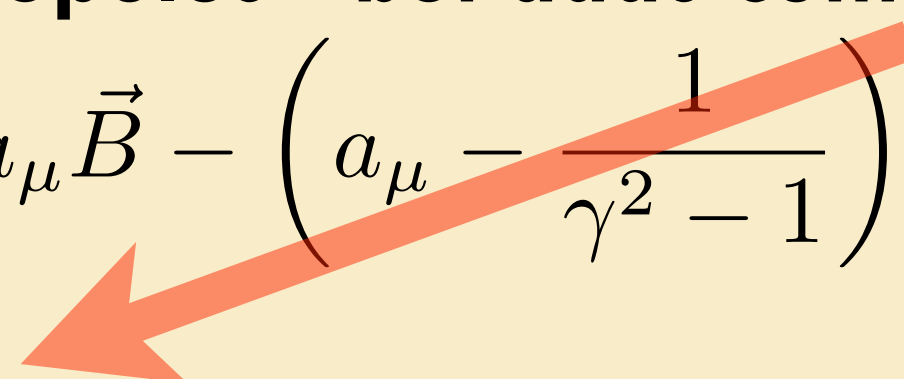
Electrostatic field introduces a radial electric field – big pain since now you have to know where the muons are – the radial fields change the g-2 frequency

A miracle happens here

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$$\vec{\omega}_a = \frac{e}{mc} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) (\vec{\beta} \times \vec{E}) \right]$$


If we choose $\gamma = 29.3$ ($p_\mu = 3.09 \text{ GeV}/c$)

then coefficient **disappears! The MAGIC momentum!**

So we can worry less about the electric field (but still will need corrections)

Had a_μ been, say 100x smaller, would need $p \sim 30 \text{ GeV}/c$

3 GeV is best – 0.5 GeV would have been too slow (not enough time dilation)
3 GeV is just right!!

An improved CERN experiment ('69-79)

Observe $N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + \phi)]$
over threshold

Fractional uncertainty is $\frac{\delta \omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a A \tau \sqrt{N}}$

Increase momentum to magic (dilates lifetime to 64 μs)

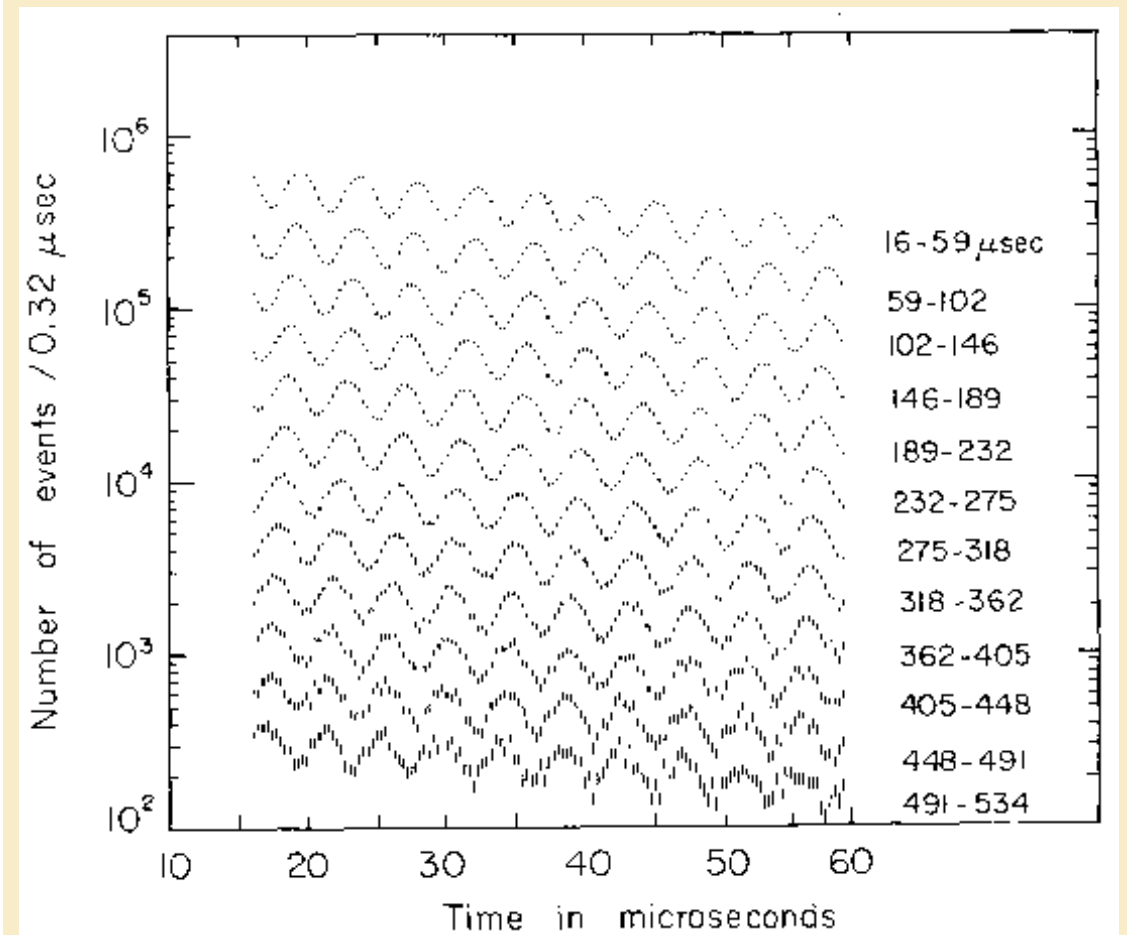
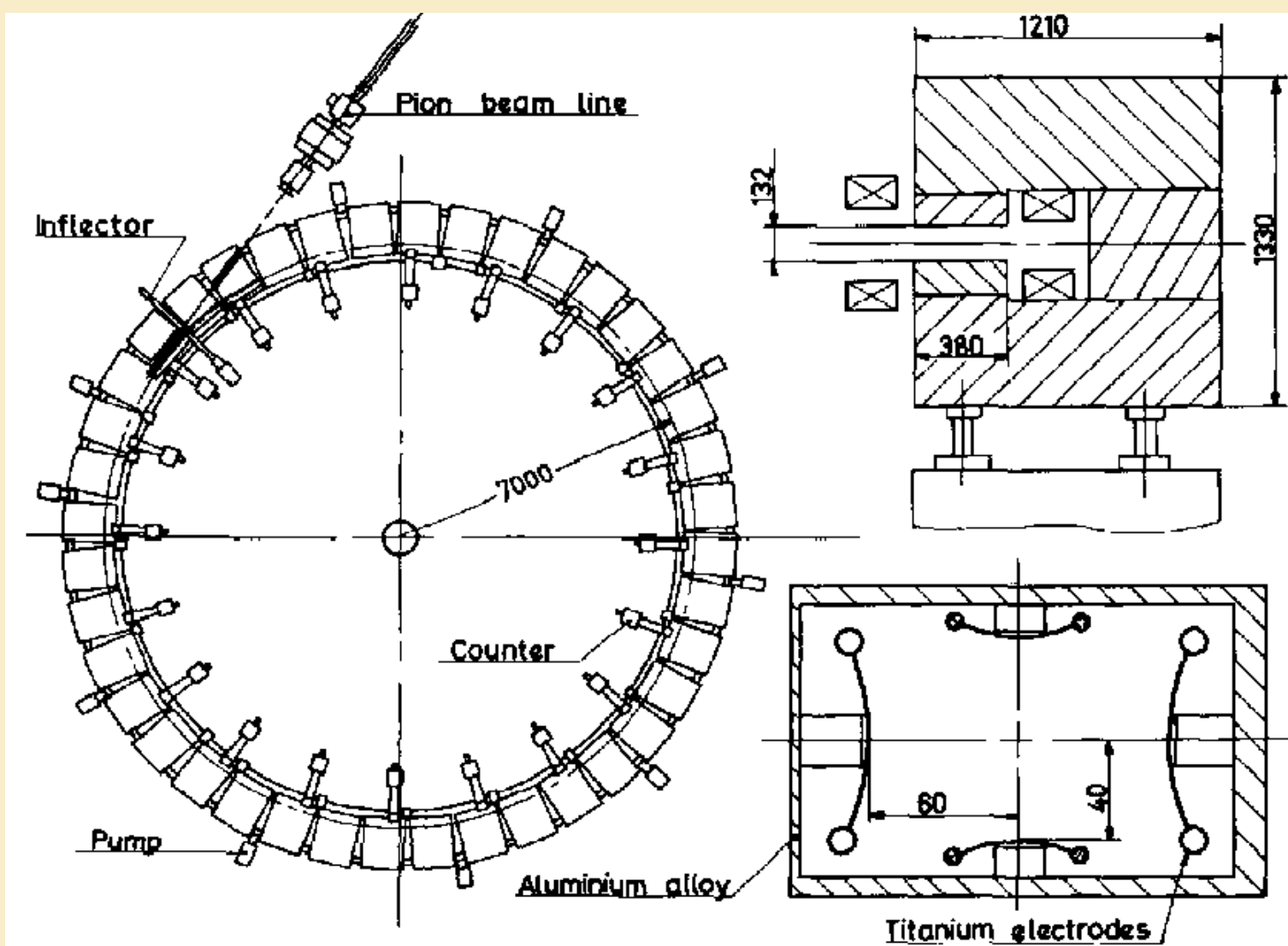
Increase *B* field, *N*

Improved λ (13 ppm to 2.6 ppm)

Target outside of ring - inject pions - better polarization

For a given positron energy cutoff

Third CERN Experiment (1979)



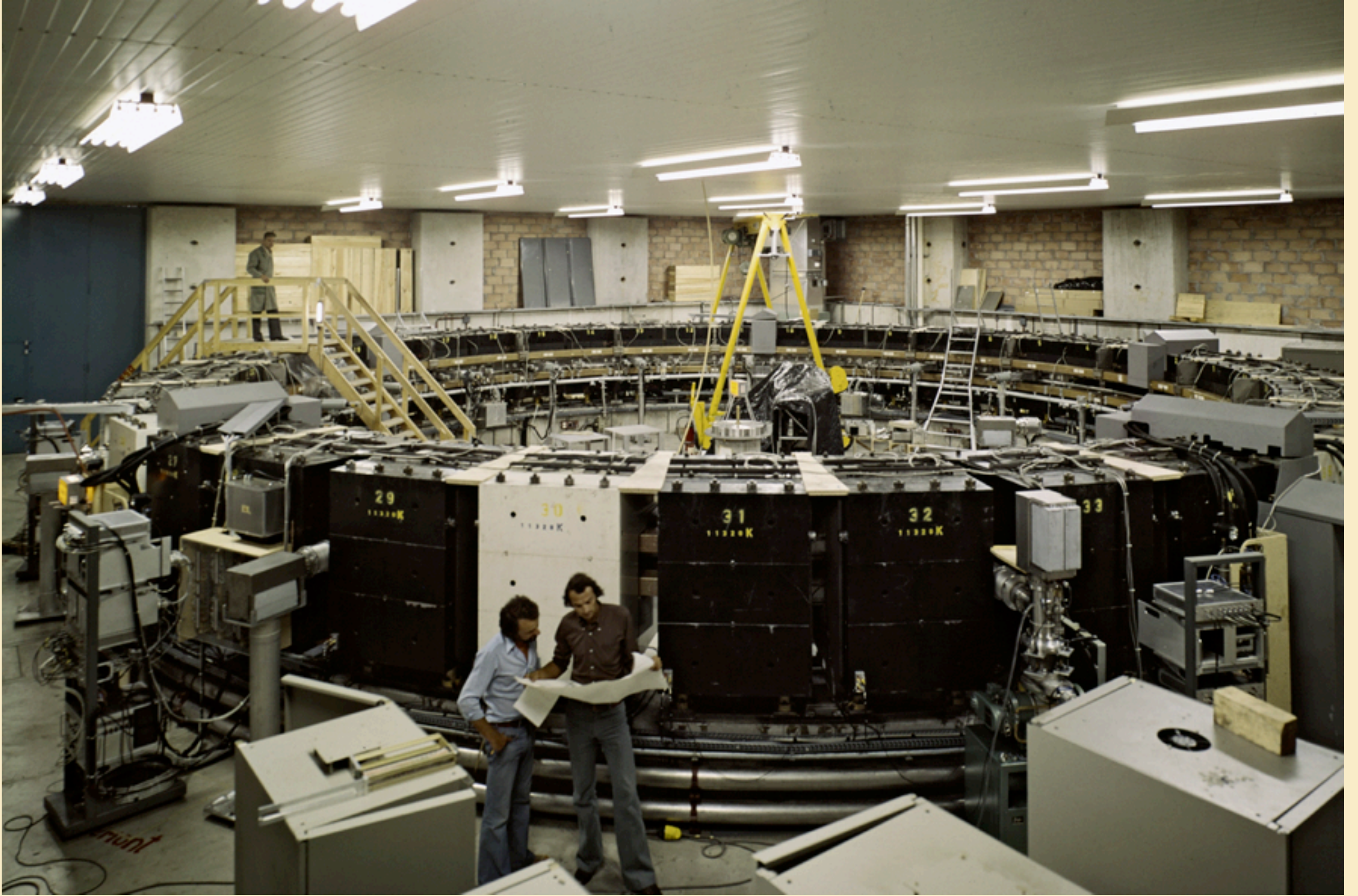
> 500 μ s

$$a_{\mu} = 0.001\,165\,924(8.5), \pm 7 \text{ ppm}$$

Sensitive to hadronic vacuum polarization (adv. muons!)

Error is dominated by statistical
Muons could only be obtained from pions that decayed in first orbit
Detectors all the way around

Third CERN g-2 Experiment



Setting the stage for Brookhaven E821

In 1984, QED was calculated to fourth order
Hadronic uncertainties were greatly reduced
Time for **new experiment** at Brookhaven at the AGS at sub ppm



Figure 1.10: A picture from 1984 showing the attendees of the first collaboration meeting to develop the BNL $g-2$ experiment. Standing from left: Gordon Danby, John Field, Francis Farley, Emilio Picasso, and Frank Krienen. Kneeling from left: John Bailey, Vernon Hughes and Fred Combley.

Improvements:

Much higher intensity

3 superconducting coils

Circular operation

Inject muons into ring with inflector and kicker

***in-situ* B measurements with NMR probes**

15 years until first pub in 1999

Brookhaven E821 g-2 Experiment

Steps of the experiment for measuring a_μ

Inject muons into the storage ring

Measure ω_a and determine corrections

Measure ω_p

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}}$$

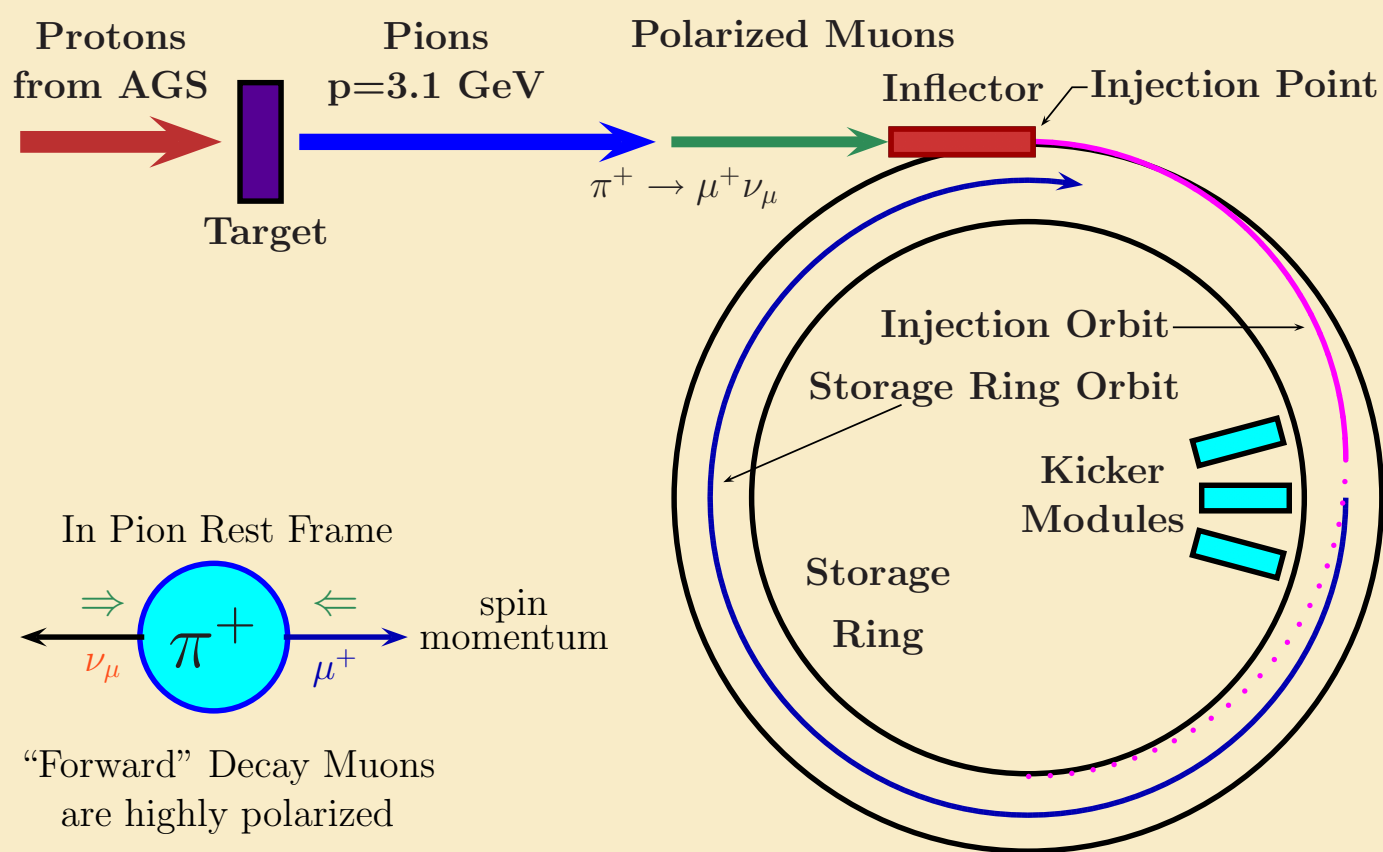
Get λ from friends

$$\mathcal{R} = \omega_a / \omega_p, \quad \lambda = \mu_\mu / \mu_p$$

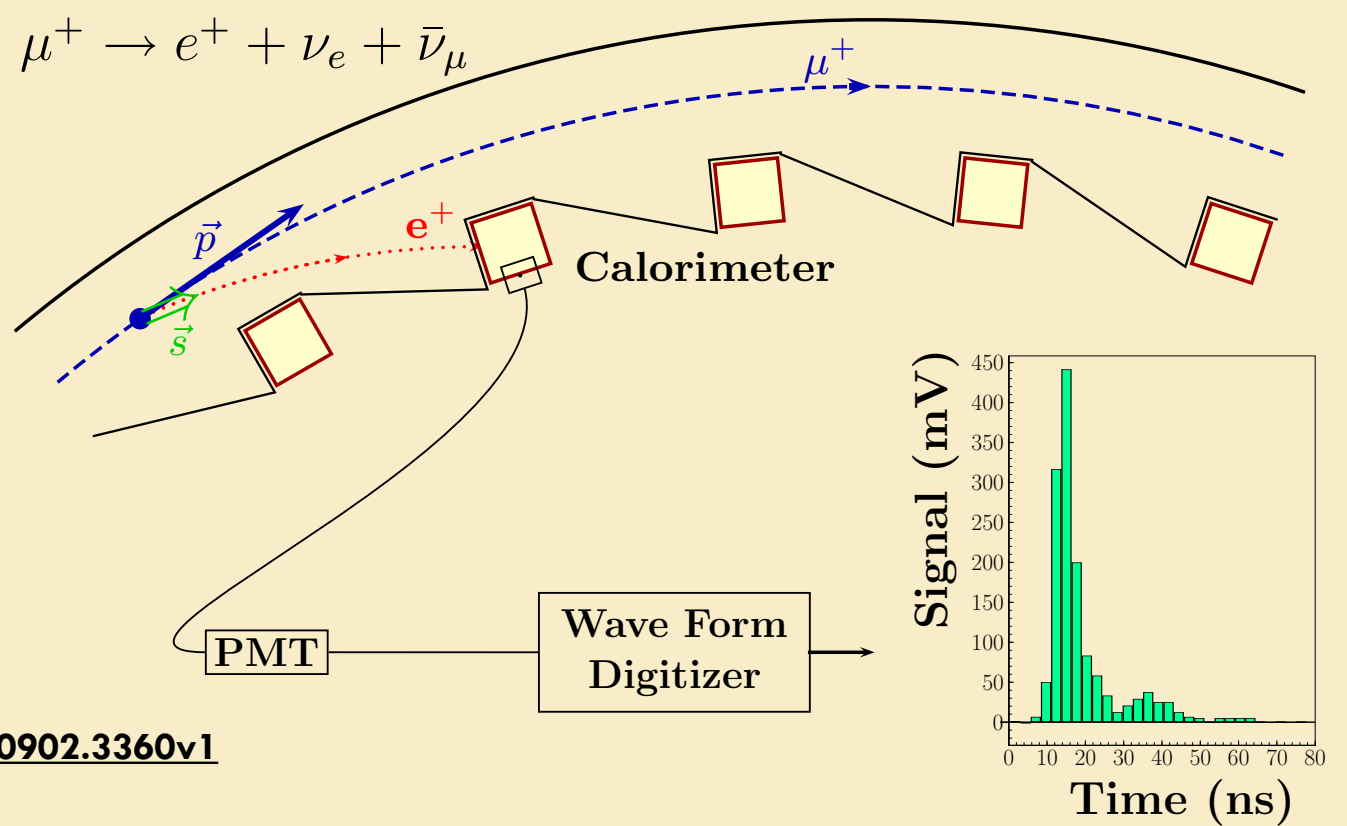
Determine systematics

Think about the next experiment

Experiment in cartoons

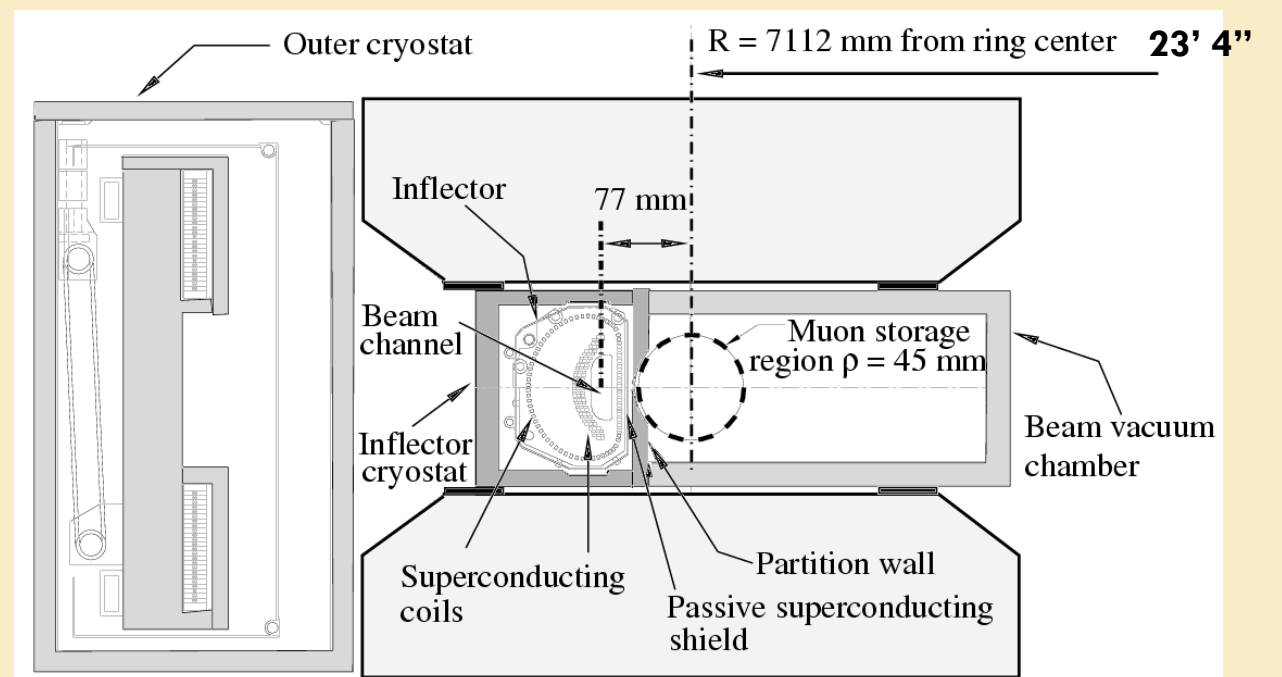
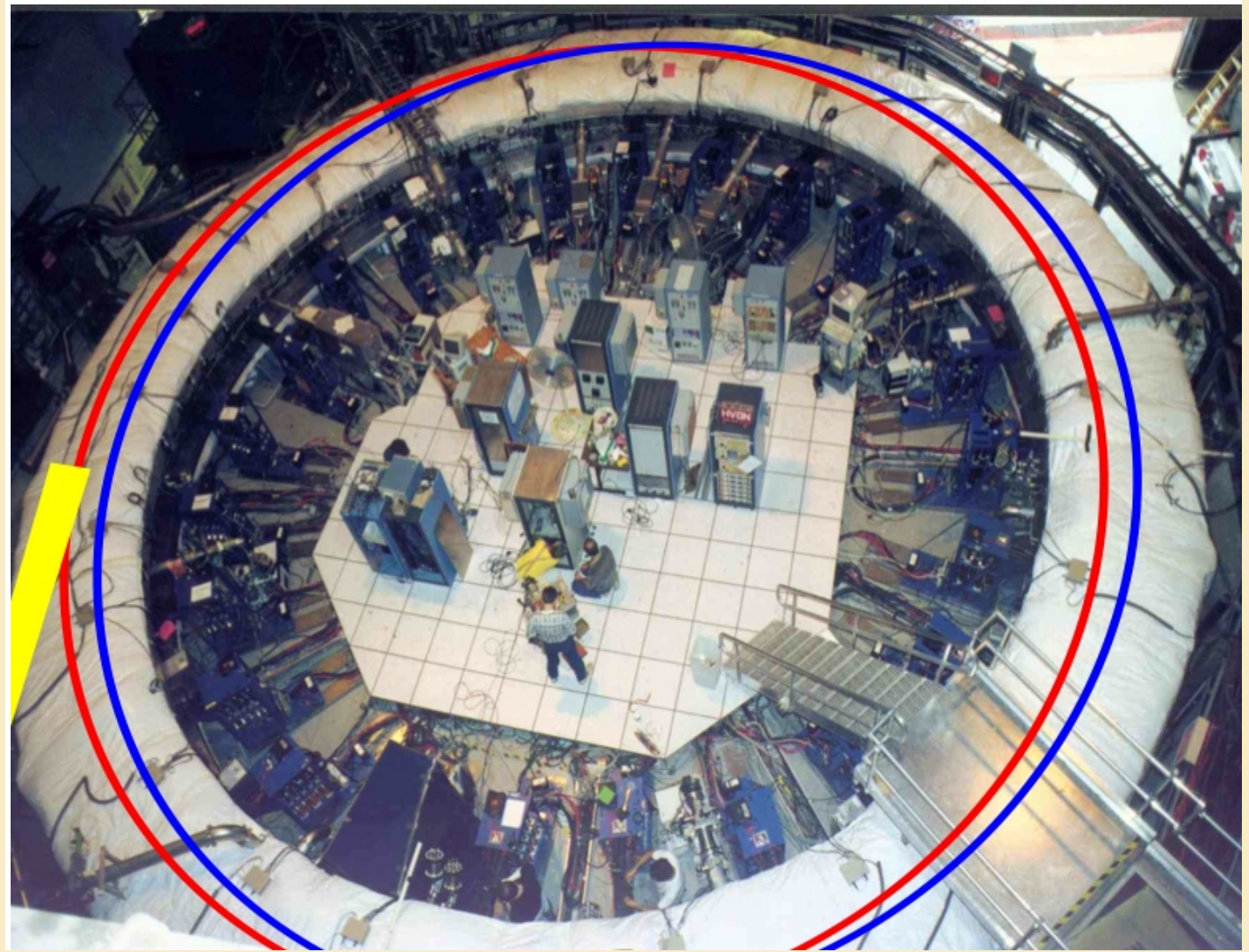
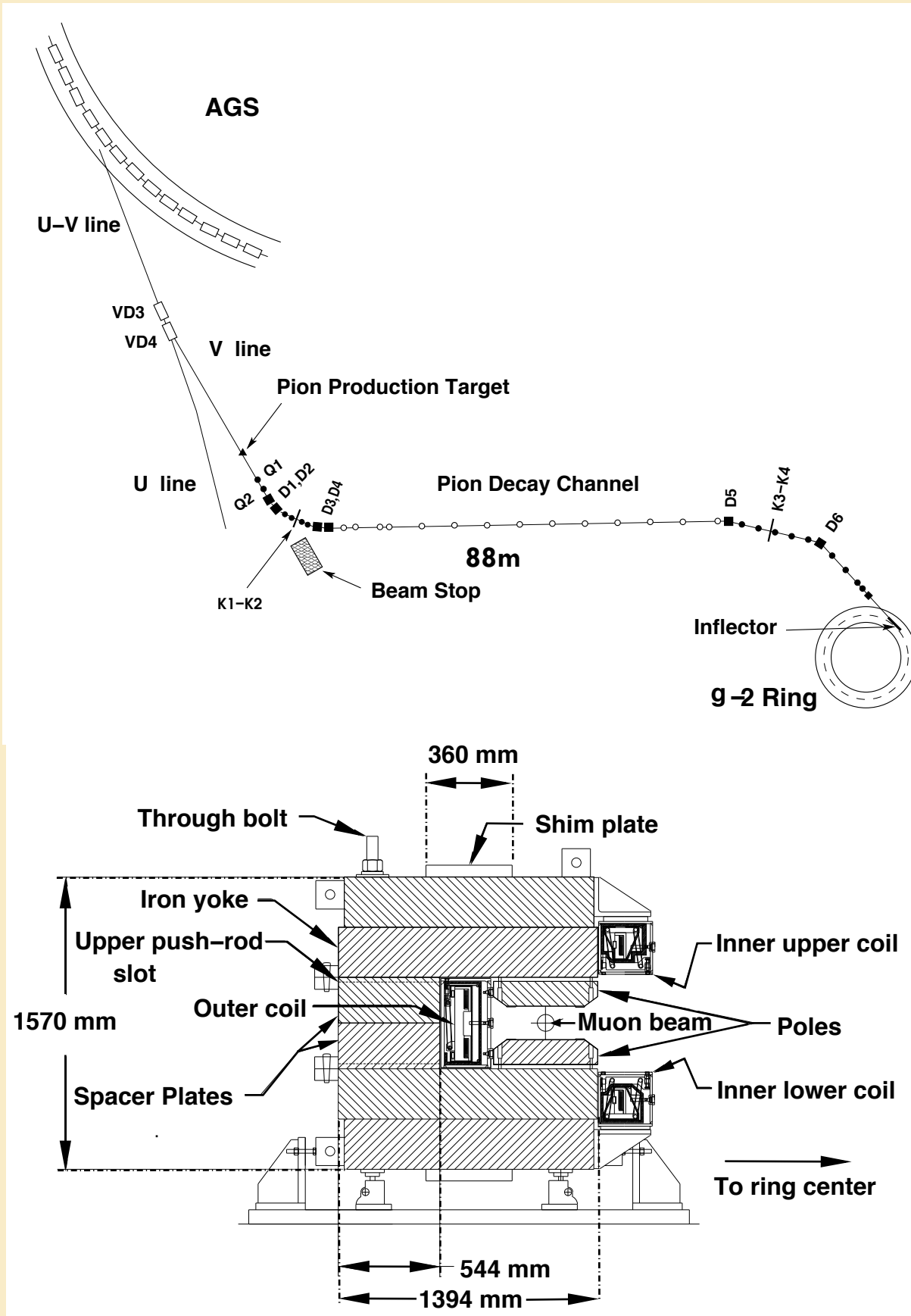


3 data runs (# e^+ 's)
1999 (950M),
2000 (4000M),
2001 (3600M e^-)
8550M events total



Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, [arXiv:0902.3360v1](https://arxiv.org/abs/0902.3360)

Injection into the storage ring



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Hadronic FLASH! In 88 m only HALF of pions decay

Muons are shot in once (they don't join a beam) – they go on the proper orbit
Kicker

10 ms between spills, 64 us lifetime take, 10 lifetimes

24 GeV protons

Water cooled nickel target

Pions at 3.115 GeV/c were selected

95% avg polarization at magic momentum of 3.09 GeV/c

Magnet is 5200A

Muon cyclotron freq 6.7 MHz (149 ns)– g-2 freq 229 KHz (4.36 microsec)

Data taking for 10 muon lifetimes – 640 microseconds

Hadronic flash

Bunch width of 25 ns, 12 bunches

The storage ring



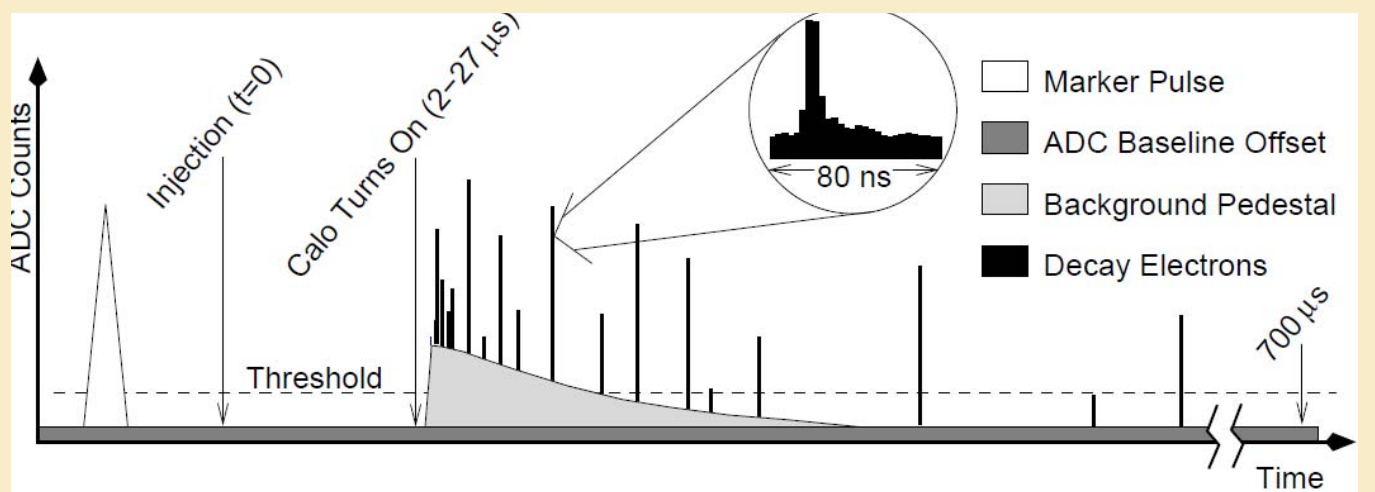
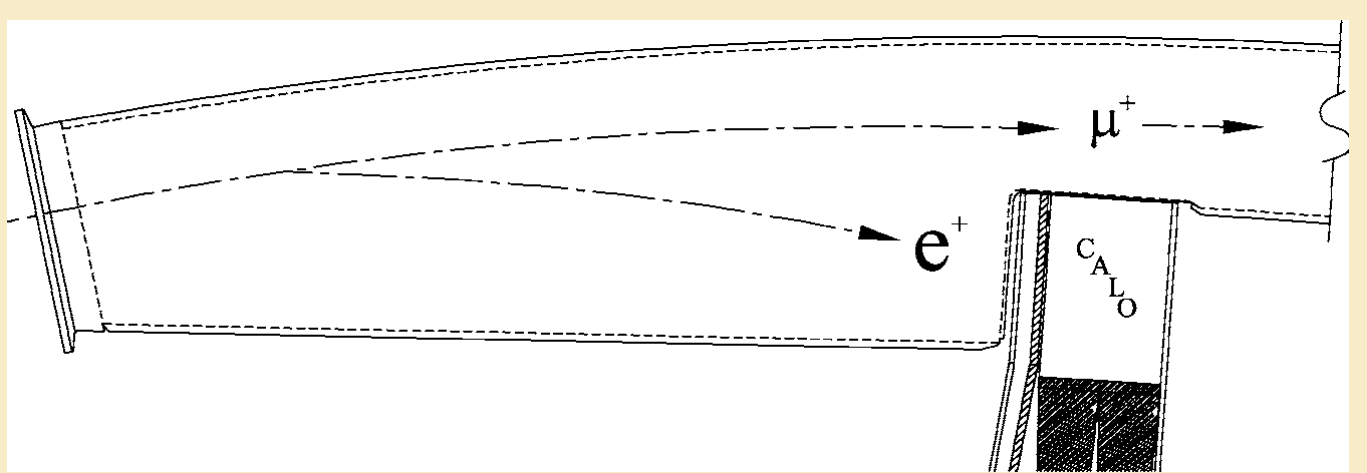
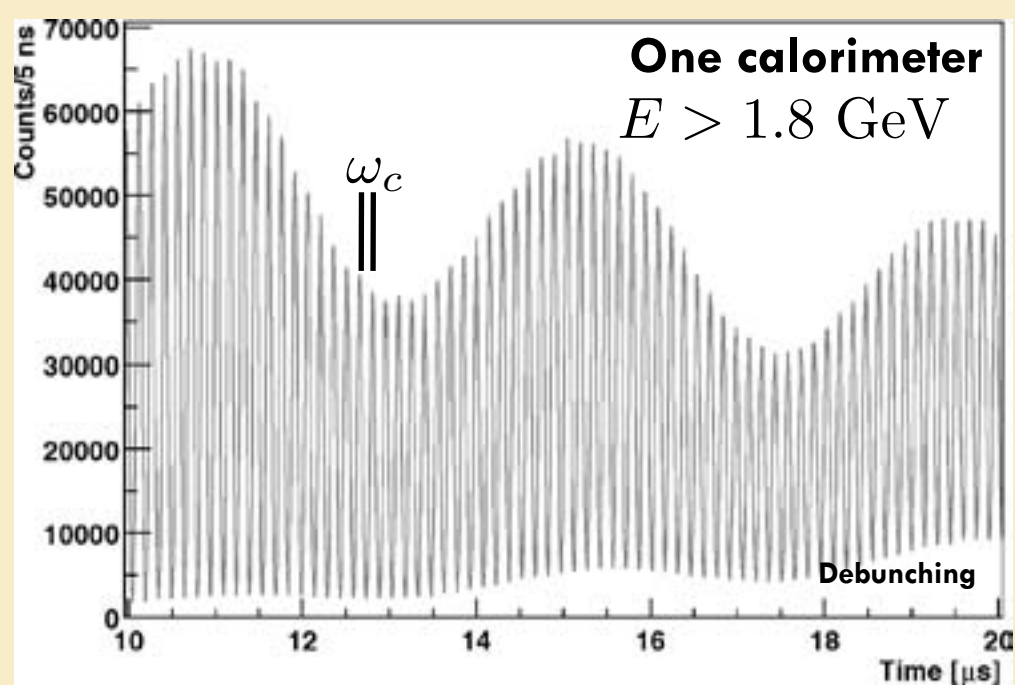
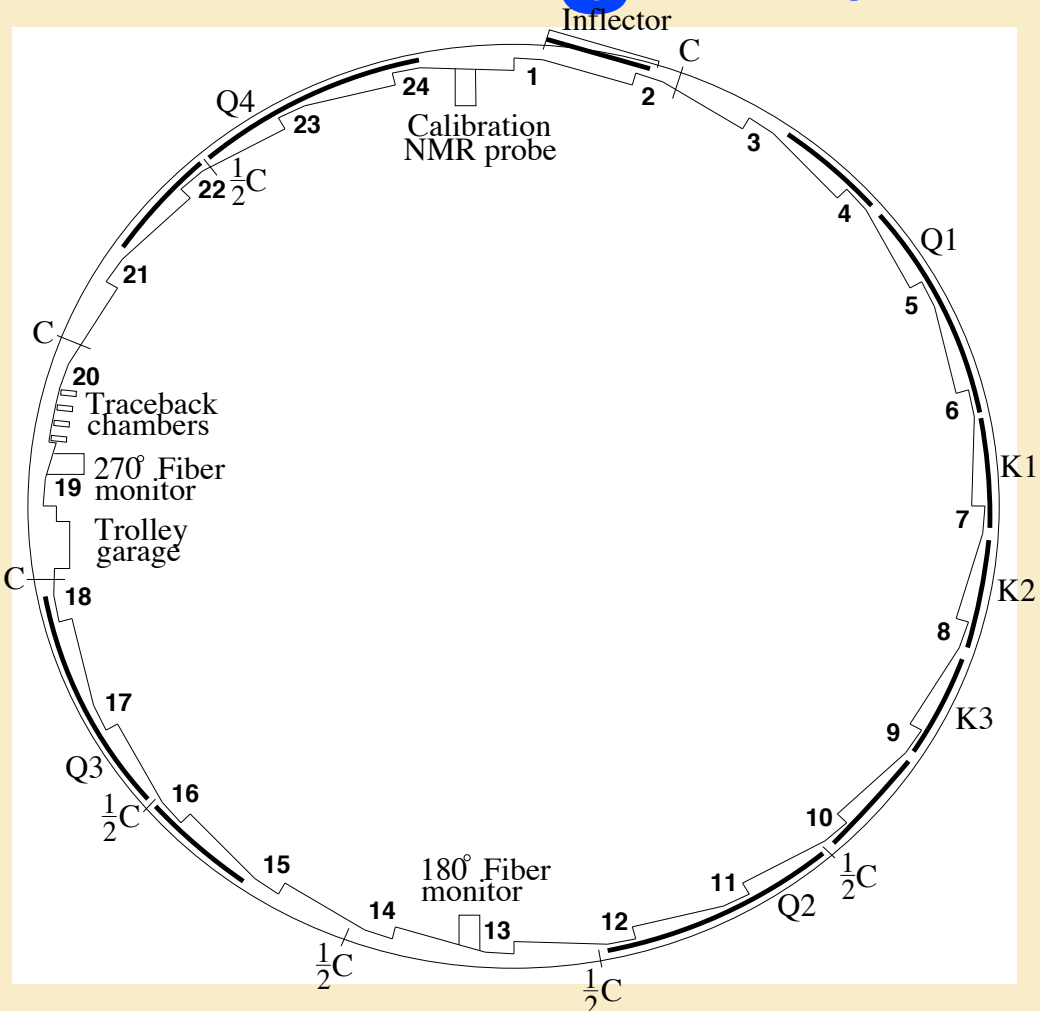
Fisheye lens

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Note strange perspective

Measuring ω_a



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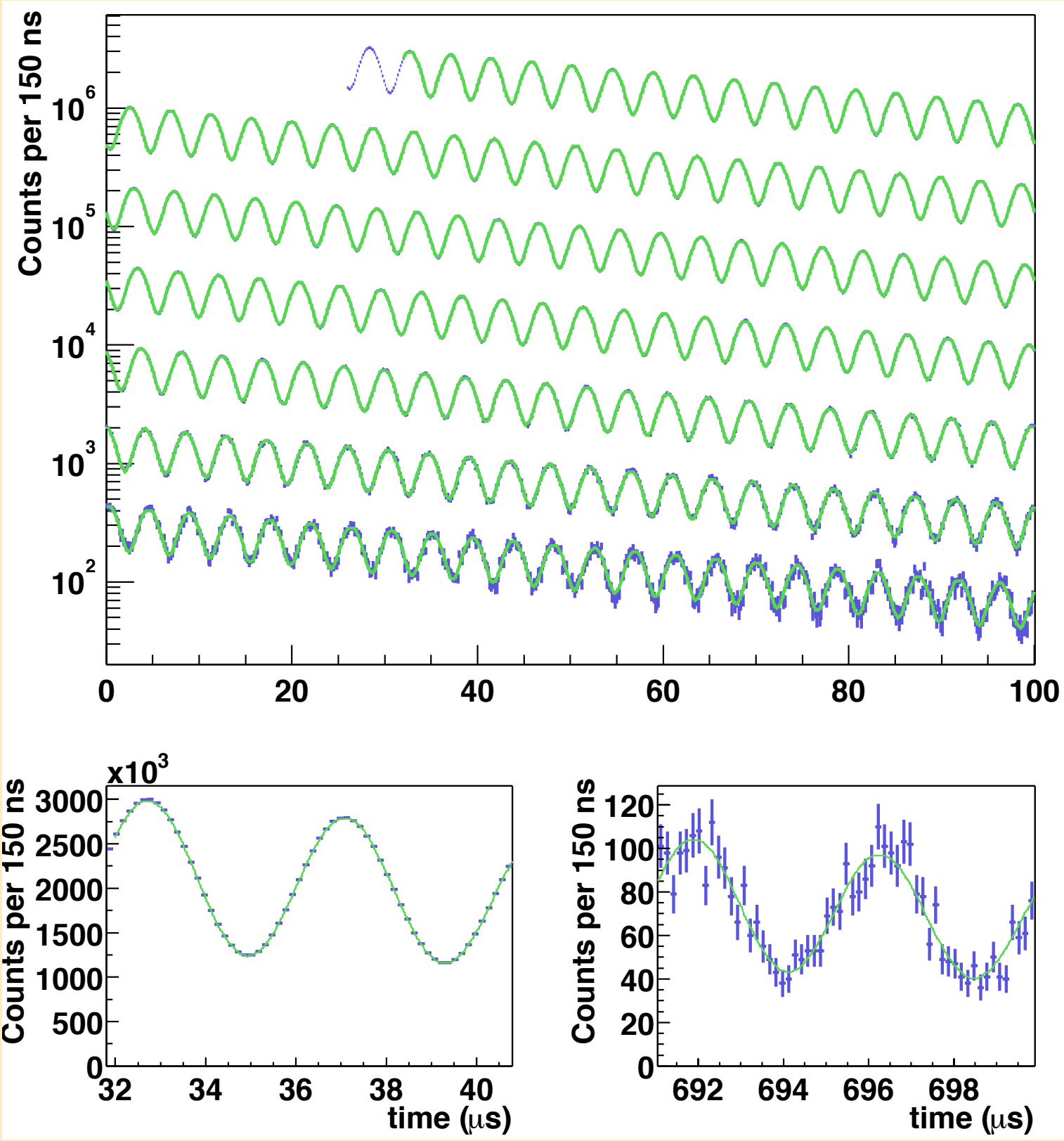
Threshold is 1.8 GeV
 Lead scintillating fiber cal
 65% efficient
 15 cm thick, 92% containment, resolution 7%/sqrt(E) (so 5% for 1.8 GeV e)
 Lower left plot is 10–20 microseconds after injection
 cyclotron period is 149ns, slow modulation is ω_a – g-2 precession – can see
 debunching of the muons (the fact that the bottom doesn't get to zero)
 Muon cyclotron freq 6.7 MHz (149 ns)– g-2 freq 229 KHz (4.36 microsec)

The 2–27 microsecond gate for flash – values range depending on location to inflector exit

Measuring ω_a

$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + \phi)]$$

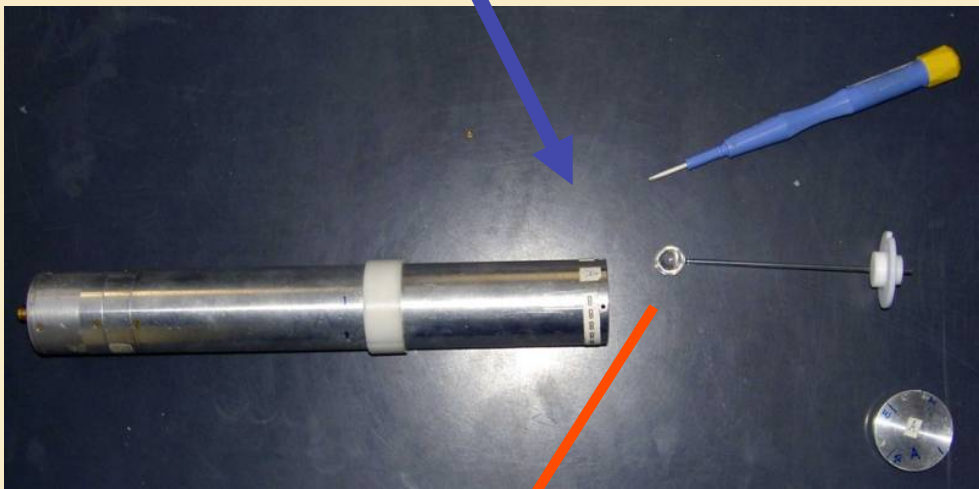
**2000 data,
4 billion decays,
5 parameter fit**



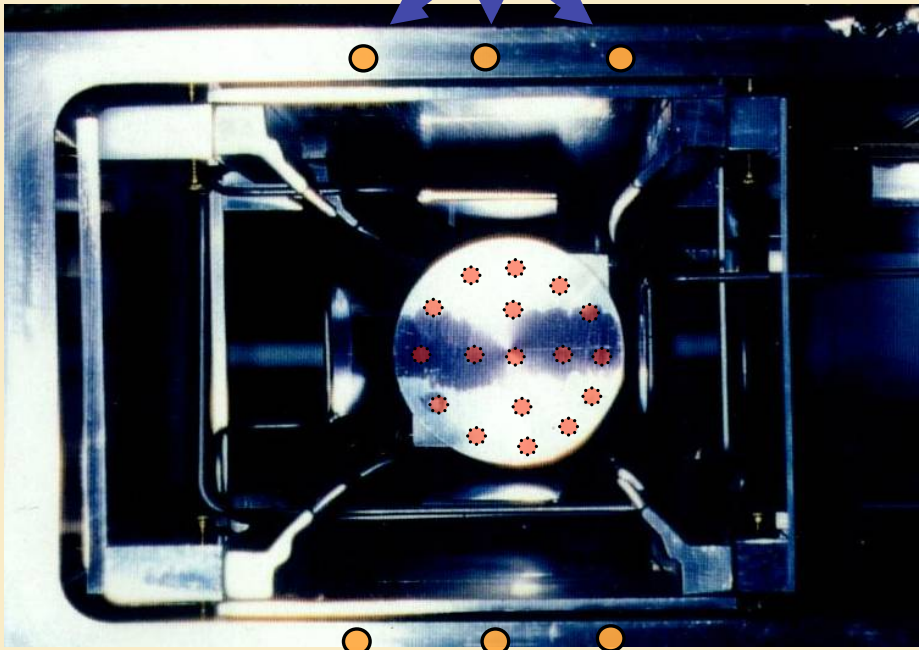
This is a fit to 5 parameters – not connecting dots. Bottom right shows this

Measuring ω_p - Measuring the B field

Absolute Calibration Probe:
a Spherical Water Sample

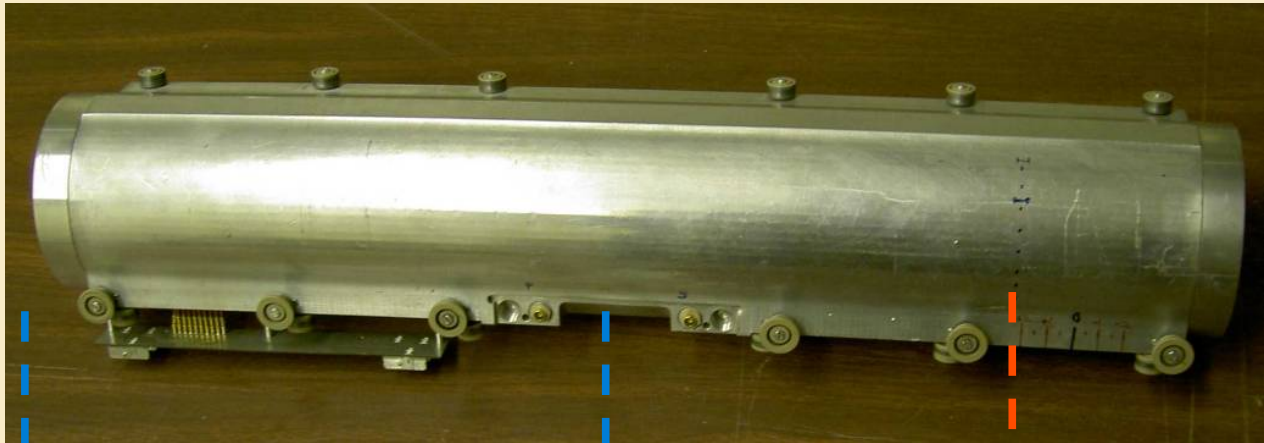


Fixed Probes in the
walls of the vacuum tank



**360 fixed
probes,
150 most
reliable**

Trolley with matrix of 17 NMR Probes

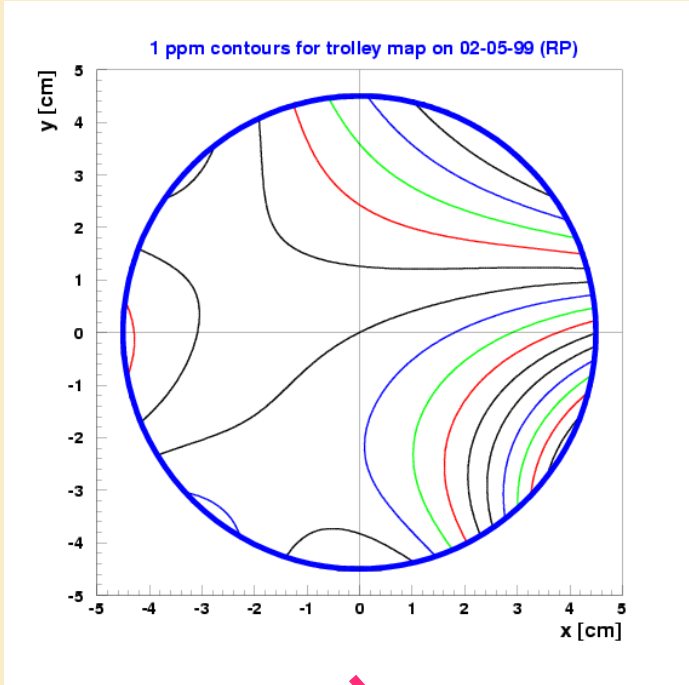


**Electronics,
Computer &
Communication**

**Position of
NMR Probes**

**In vacuum, 6000 azimuthal measurements,
Calibrated against plunging probe**

Measuring ω_p - Shimming the field

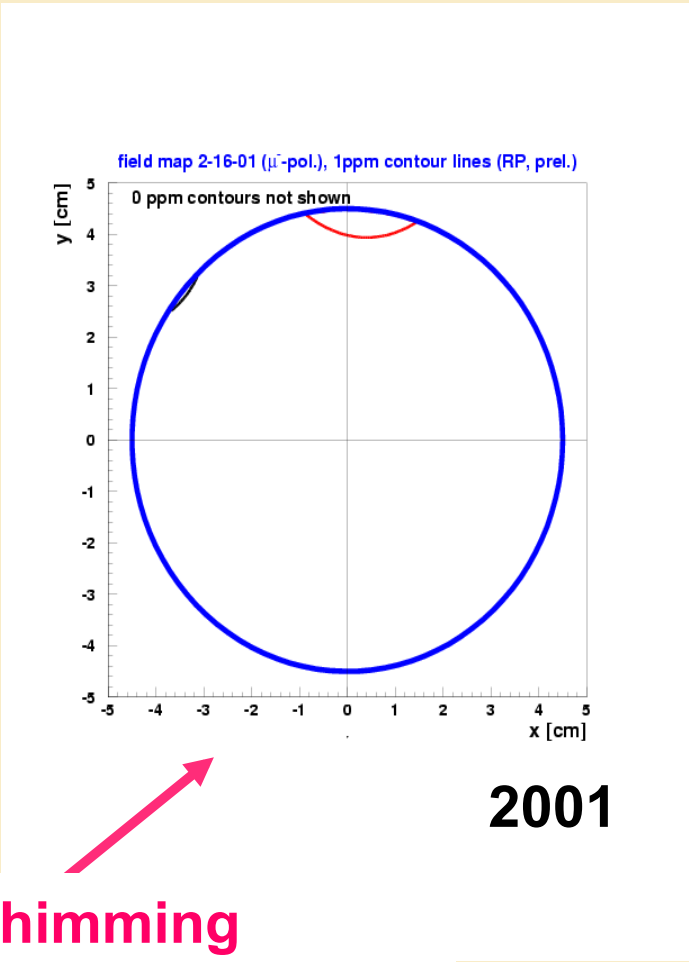
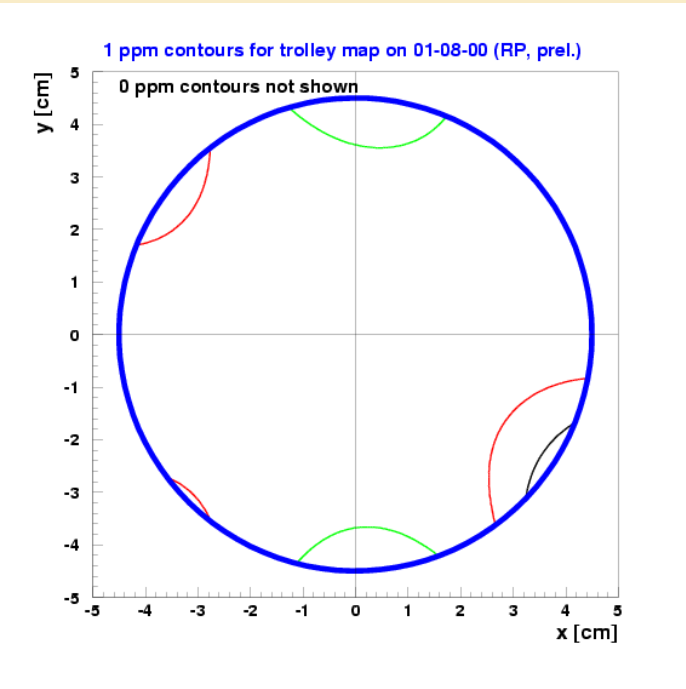


1999

shimming

1 ppm contours are
avg of B over 2π
in muon storage
region 10cm x 10cm

2000



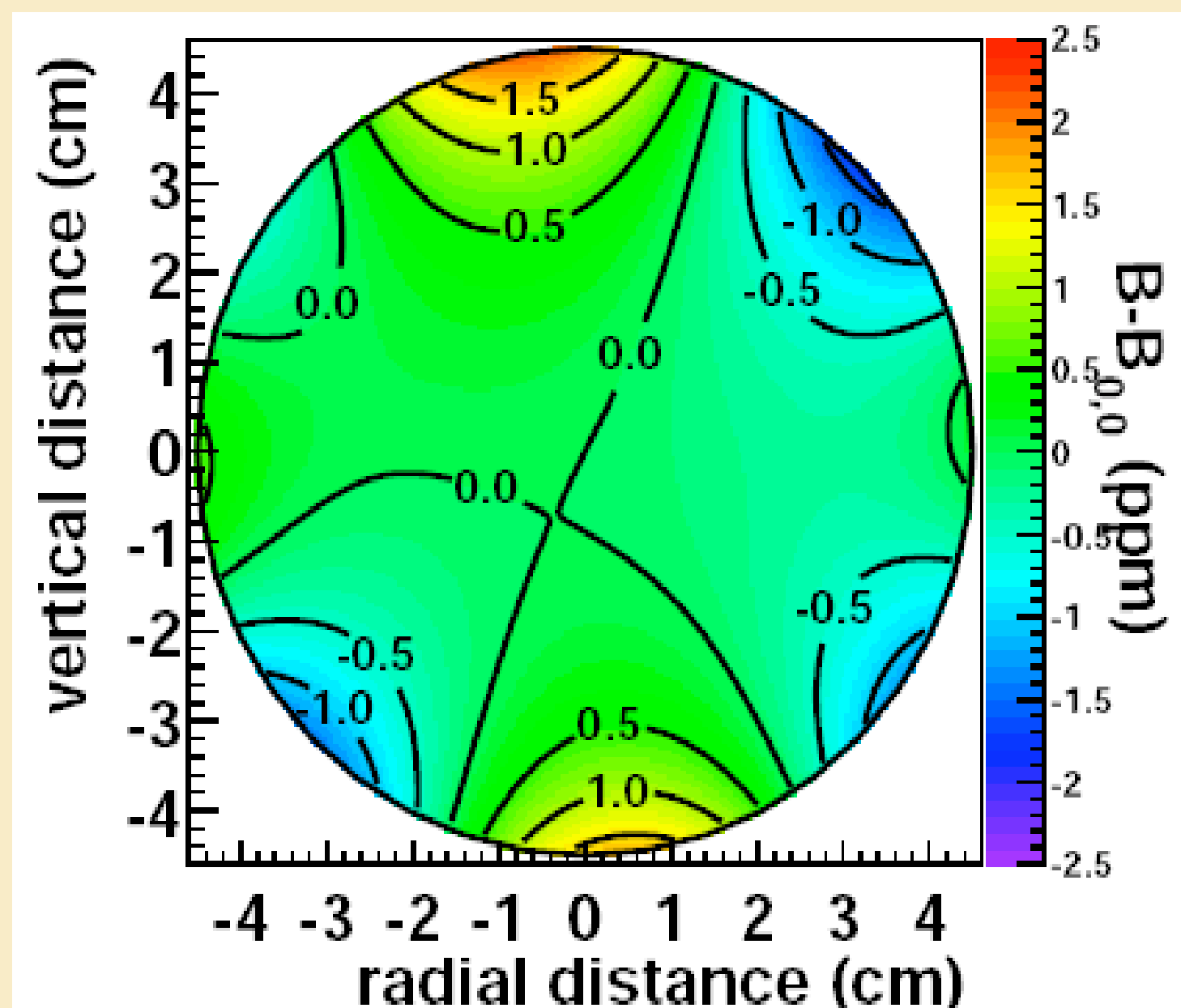
2001

shimming

Measuring ω_p

**Blind analysis with
separate groups (no
one person knows both
 ω_a and ω_p)**

$\lambda = 3.18334539(10)$
Led by Hughes at LAMPF



Systematics

$\sigma_{\text{syst}} \omega_p$	1999	2000	2001	$\sigma_{\text{syst}} \omega_a$	1999	2000	2001
	(ppm)	(ppm)	(ppm)		(ppm)	(ppm)	(ppm)
Inflector fringe field	0.20	-	-	Pile-Up	0.13	0.13	0.08
Calib. of trolley probes	0.20	0.15	0.09	AGS background	0.10	0.01	‡
Tracking B with time	0.15	0.10	0.07	Lost muons	0.10	0.10	0.09
Measurement of B_0	0.10	0.10	0.05	Timing shifts	0.10	0.02	‡
μ -distribution	0.12	0.03	0.03	E-field/pitch	0.08	0.03	‡
Absolute calibration	0.05	0.05	0.05	Fitting/binning	0.07	0.06	‡
Others [†]	0.15	0.10	0.07	CBO	0.05	0.21	0.07
				Beam debunching	0.04	0.04	‡
				Gain changes	0.02	0.13	0.12
Total for ω_p	0.4	0.24	0.17	Total for ω_a	0.3	0.31	0.21

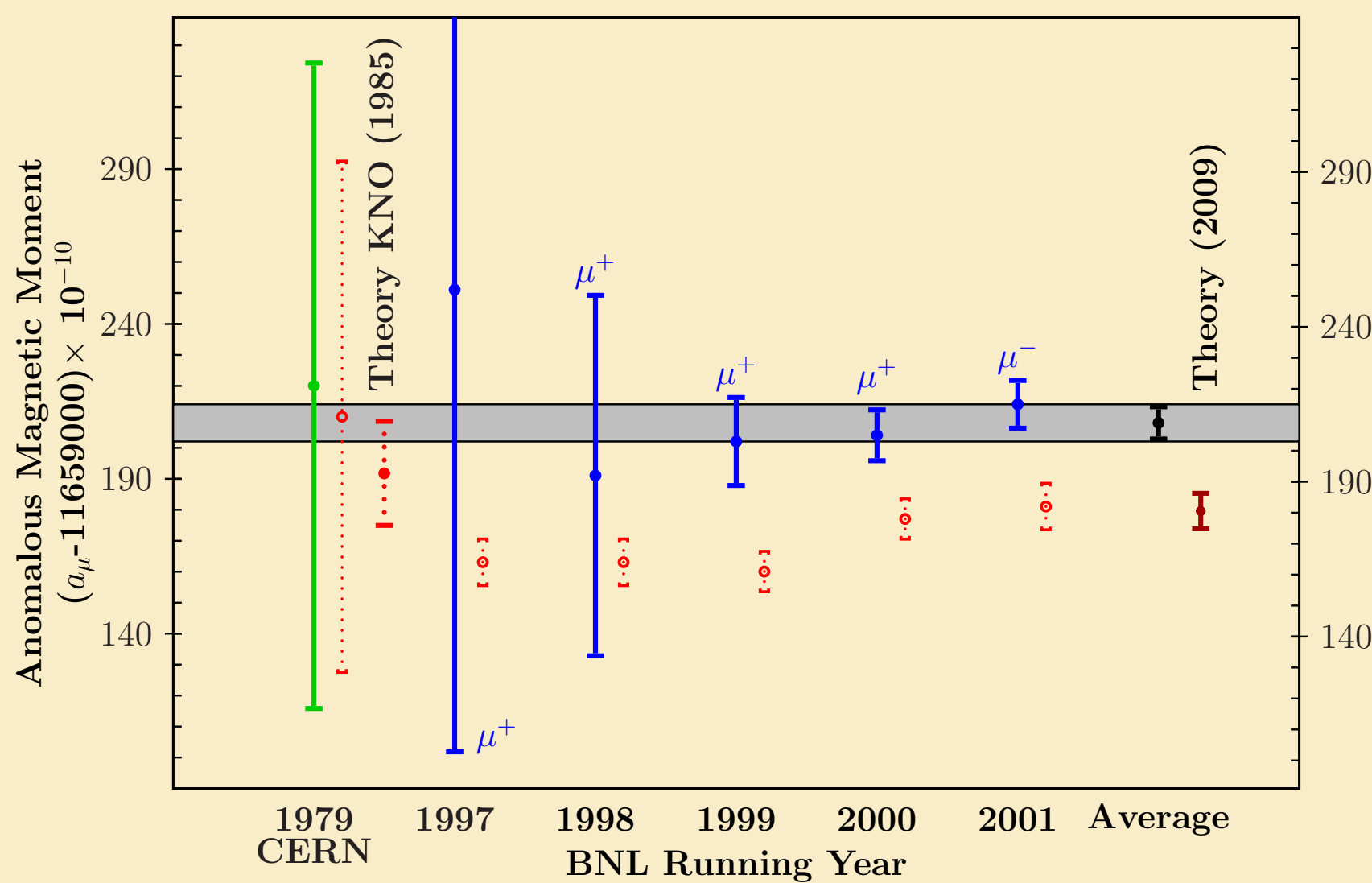
Total 0.28 ppm systematic

Double dagger means these were calculated together to be 0.11 ppm

dagger – Others for omega p = trolley temperature, power supply voltage response, higher order modes

$$a_{\mu}^{\text{exp}} = 116\,592\,089(63) \times 10^{-11} \text{ (0.54 ppm)}$$

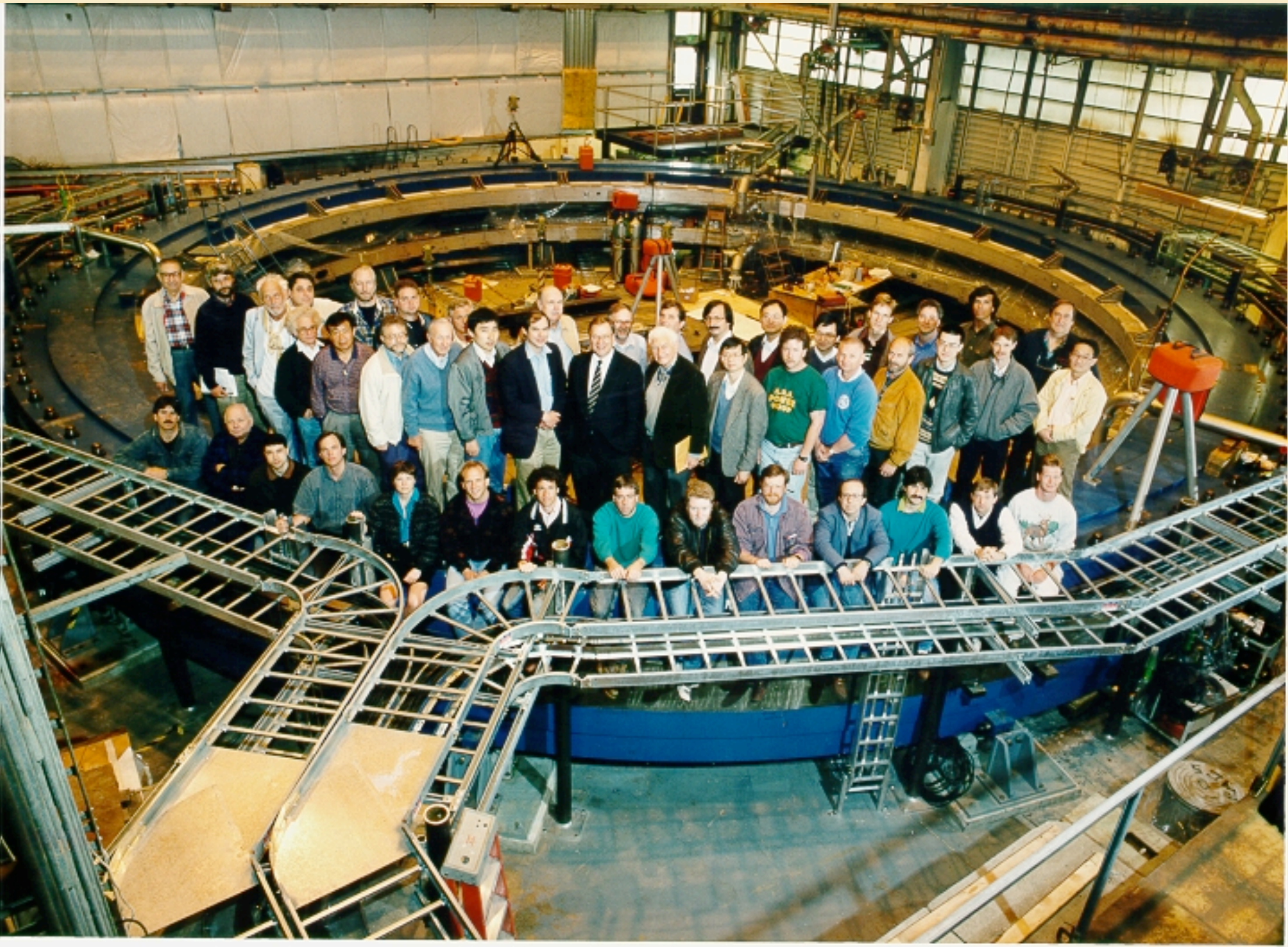
0.46 ppm statistics, 0.28 ppm systematic



$$g_{\mu}^{\text{exp}} = 2.002\,331\,841\,78(126)$$

mu- run is really important - flipped B field and different E field and lower losses
Original result was 080 - but became 089 later when lambda was updated

A Job Well Done



Lyon - New g-2 - ANL - 2012-01

Comparing to Theory

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{had}} + a_{\mu}^{\text{weak}} + a_{\mu}^{\text{???}}$$

1st order QED

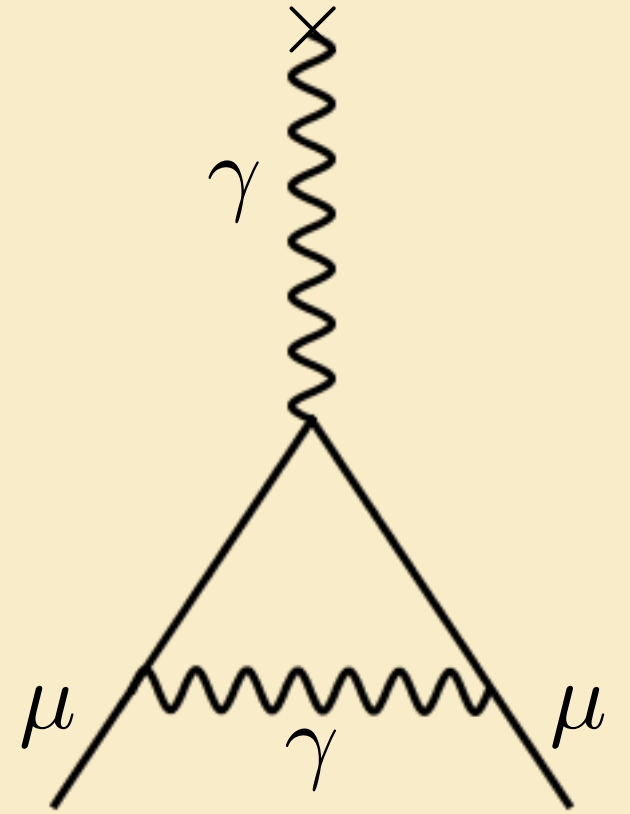
$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{had}} + a_{\mu}^{\text{weak}} + a_{\mu}^{\text{???}}$$

Lowest order QED is

$$a_{\mu}^{\text{LO QED}} = \alpha/2\pi = 0.00118$$

$$a_{\mu}^{\text{exp}} = 0.00116592089(63)$$

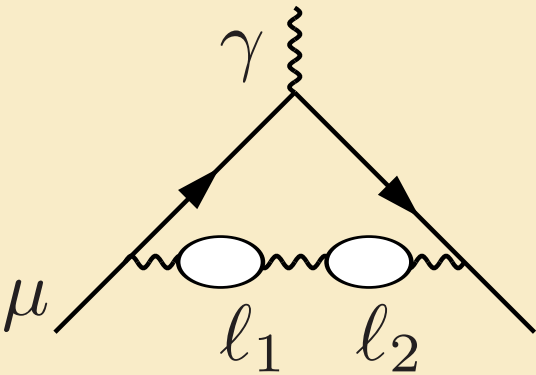
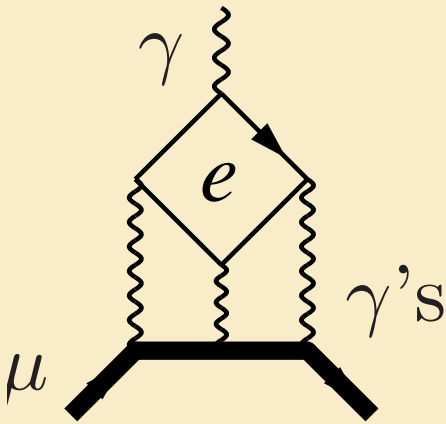
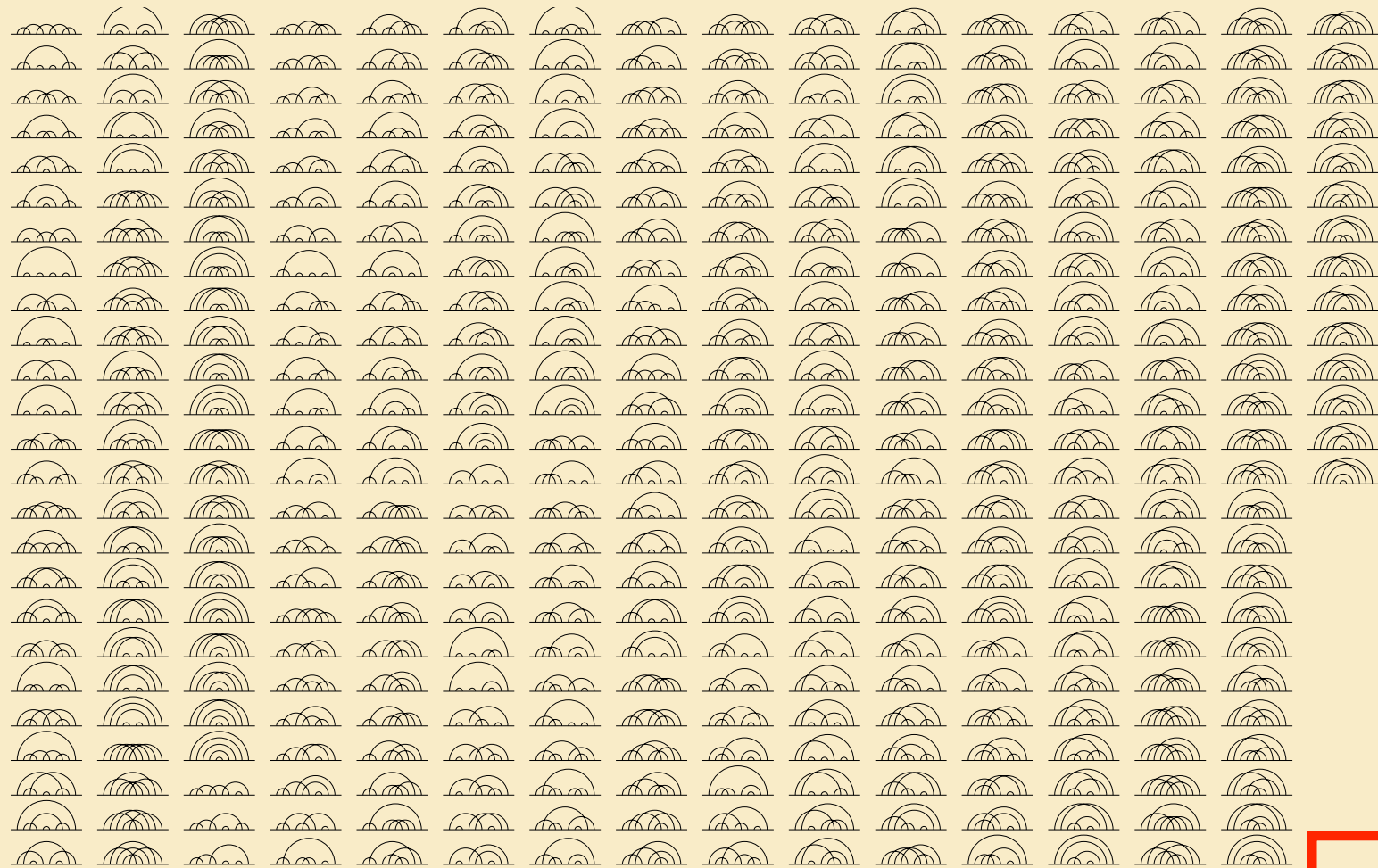
$$a_{\mu}^{\text{LO QED}} = 0.00118$$



QED contributions

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{had}} + a_{\mu}^{\text{weak}} + a_{\mu}^{???}$$

QED corrections computed to $O(\alpha^4)$ including 10th order term (12,672 diagrams contribute)



T. Kinoshita

$$a_{\mu}^{\text{exp}} = 0.00116592089(63)$$

$$a_{\mu}^{\text{QED}} = 0.0011658471809(15)$$

381 that contribute to 10th order term
LBL and vac polarization

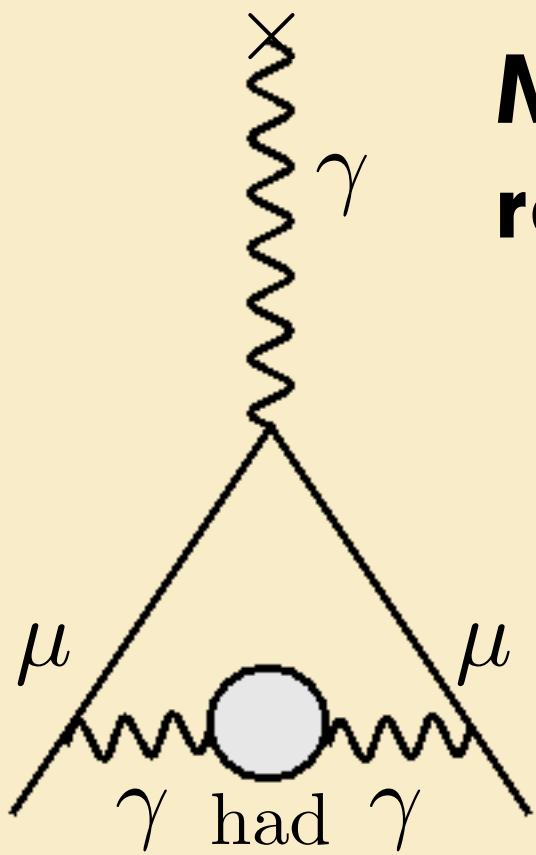
0.0011658471
0.0000000693

Hadronic contributions

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + \boxed{a_{\mu}^{\text{had}}} + a_{\mu}^{\text{weak}} + a_{\mu}^{???}$$

Hadronic contribution has the largest uncertainty

Three parts: 1st & 2nd = HVP(LO) & HVP(NLO)



Most from low energy nonperturbative QCD regime (needs experimental inputs)

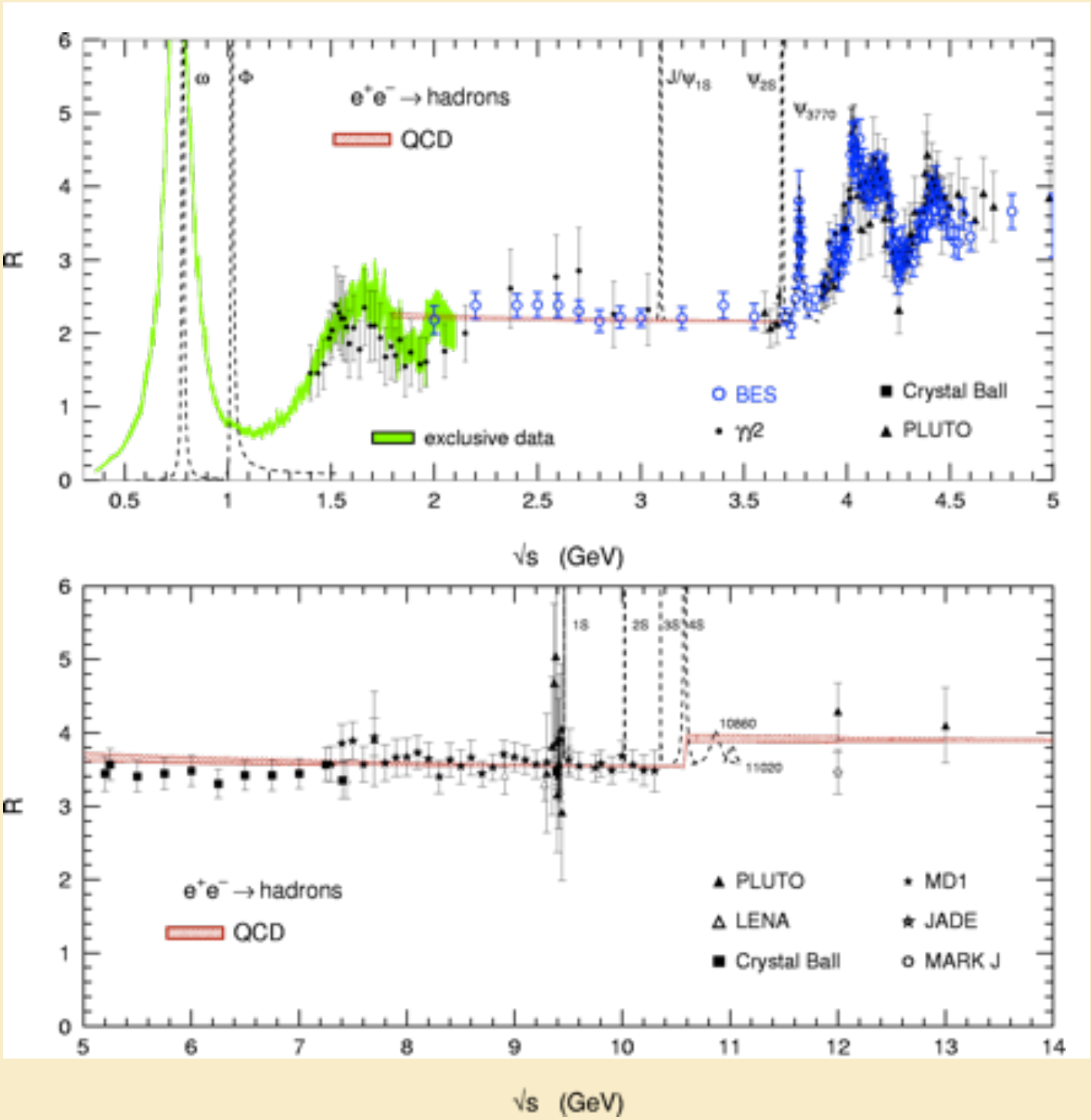
$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s),$$

$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

R(s) input to HVP(LO)

Requires precision $e^+e^- \rightarrow \text{hadrons}$

A whole industry built to measure R



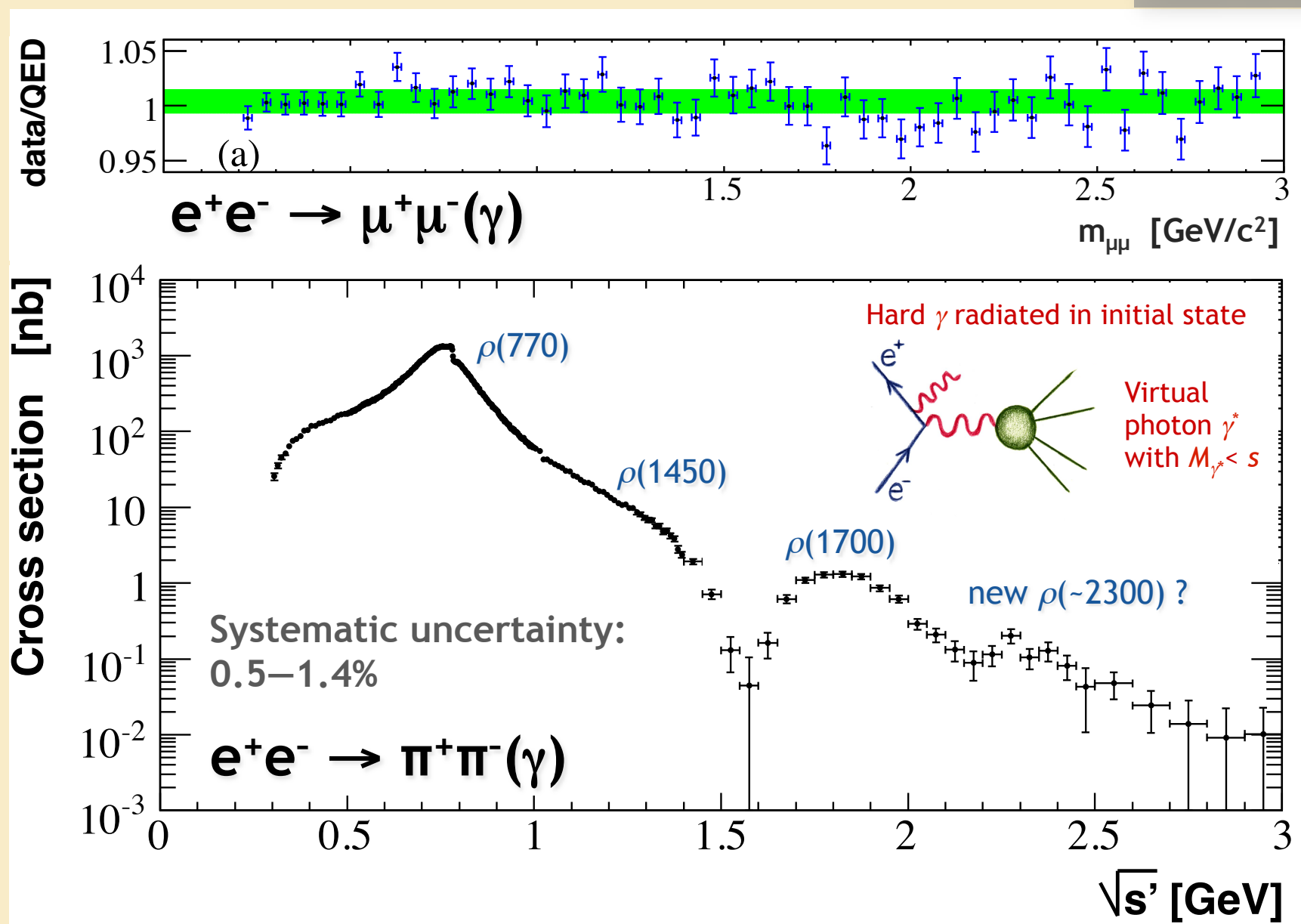
M. Davier ICFA 2011

Most of what counts is on the low end!!

R(s) input to HVP(LO)

Requires precision $e^+e^- \rightarrow \text{hadrons}$

BABAR:



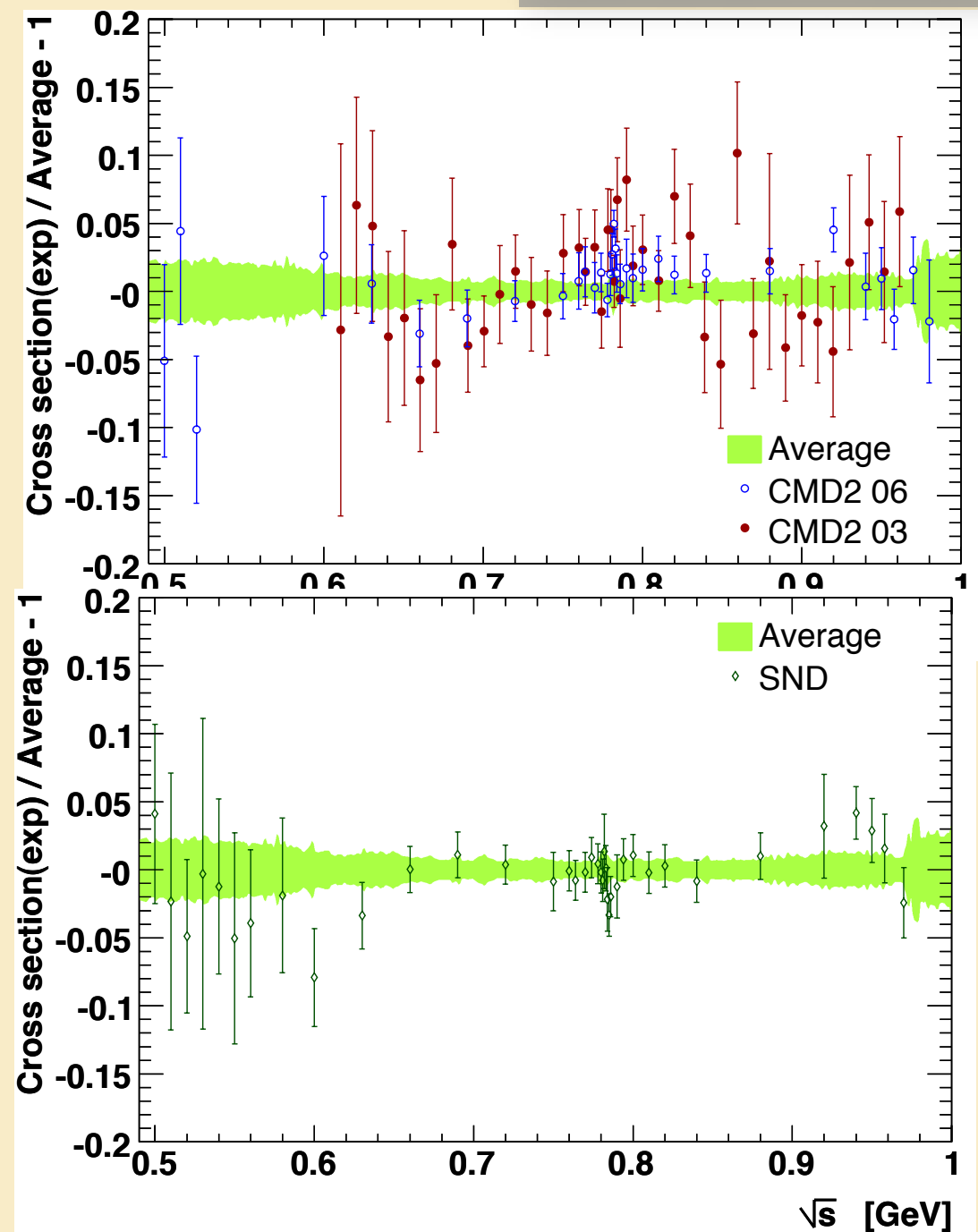
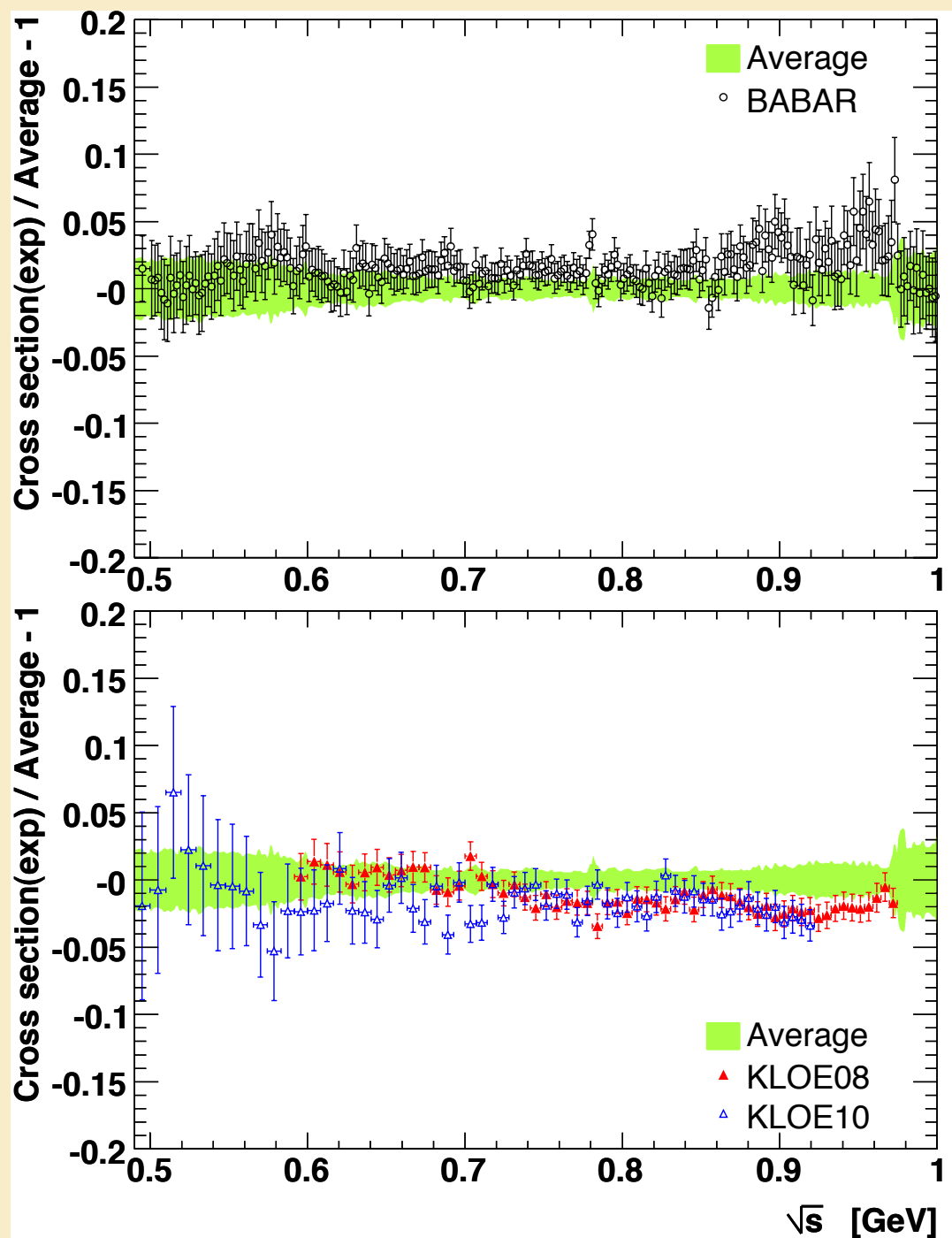
M. Davier ICFA 2011

1 –2 GeV region new and much better

R(s) input to HVP(LO)

Requires precision $e^+e^- \rightarrow \text{hadrons}$

Davier et al., EPJ C 71, 1515 (2011)



Most of what counts is on the low end!! But some tension above 0.9

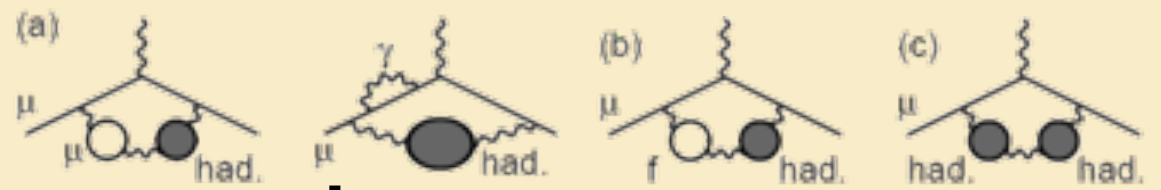
HVP(LO & NLO)

Results from taus compare well too, but with some differences

Huge 15 year effort has paid off with factor of 4 error reduction

Prospects for even more improvements are good

- New VEPP-2000 at Novosibirsk
(x10-100 better stats, energy up to 2 GeV)
- New CMD3 and SND2000 detectors



HVP(NLO) is similar and uses much of the same data

$$a_{\mu}^{\text{HVPLO}} = (692.3 \pm 4.2) \times 10^{-10}$$
$$a_{\mu}^{\text{HVPNLO}} = (-9.8 \pm 0.1) \times 10^{-10}$$

M. Davier, Hagiwara

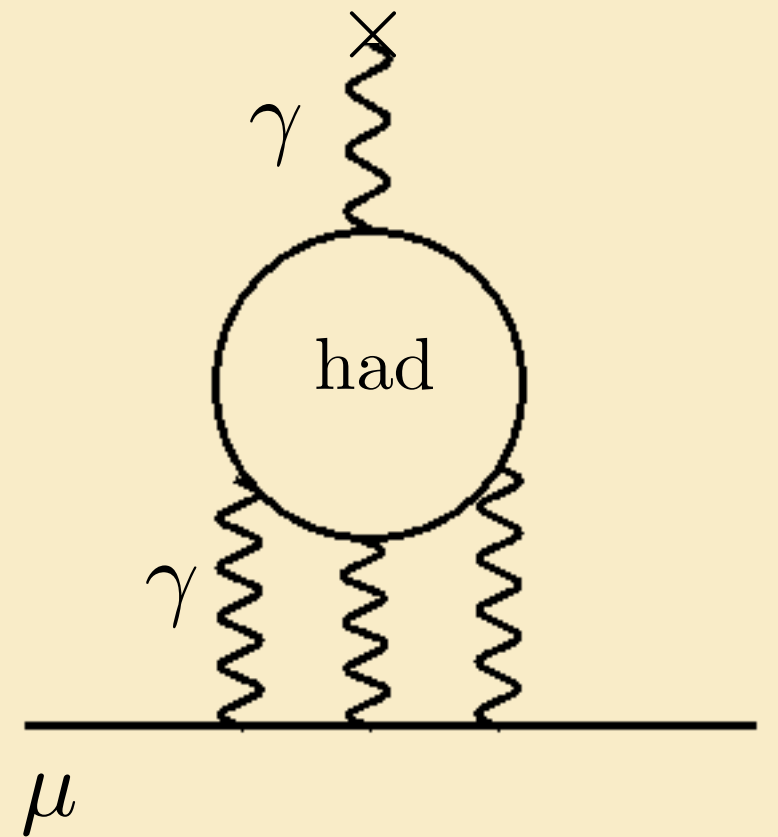
Hadronic light-by-light

Model dependent calculations

Now an industry!

Future prospects:

**KLOE to measure $\gamma^* \gamma^* \rightarrow \text{hadrons}$
at $q^2 \sim 0$ will provide first constraints**



Lattice QCD calculations are under study

$$a_{\mu}^{\text{HLBL}} = (10.5 \pm 2.6) \times 10^{-10}$$

Prades, deRafael, Vainshtein (and others)

Was a sign error discovered in 2002, but other than that stable for past 10 years
Called light by light because the blob represents photon-photon scattering

INT Workshop on The Hadronic Light-by-Light Contribution to the Muon Anomaly, Feb 2011, UWash

Date	Speaker	Powerpoint or .pdf	Podcast
February 28, 2011	D. Hertzog	"Welcome and Introductory Remarks"	No Podcast Available
February 28, 2011	L. Roberts	"Goals and Perspectives on the New g-2 Experiment"	No Podcast Available
February 28, 2011	H. Bijmans	"Hadronic Light-by-Light: Extended Nambu-Jona-Lasinio and Chiral Quark Models"	No Podcast Available
February 28, 2011	A. Nyffeler	"Hadronic light-by-light scattering in the muon g-2: Chiral approach and resonance dominance"	No Podcast Available
February 28, 2011	A. Vainshtein	"Comments on Recent Developments in Theory of Hadronic Light-by-Light"	No Podcast Available
March 1, 2011	O. Catà	"Holographic QCD and HLbL"	No Podcast Available
March 1, 2011	D.K. Hong	"Holographic Models of QCD and Muon g; - 2 "	No Podcast Available
March 1, 2011	M. Ramsey-Musolf	"Hadronic LBL: Insights from γ Symmetry"	No Podcast Available
March 1, 2011	R. Williams	"HLbL from a Dyson-Schwinger Approach"	No Podcast Available
March 1, 2011	T. Blum	"Hadronic light-by-light contribution to the muon g-2 from lattice QCD+QED"	No Podcast Available
March 1, 2011	S. Hashimoto	"$\pi^0 \rightarrow \gamma^* \gamma^*$"	No Podcast Available
March 1, 2011	K. Jansen	"Hadronic Vacuum Polarization Contribution to g-2 from the Lattice"	No Podcast Available
March 1, 2011	A. Kronfeld	"The Exascale Era and What to Expect in 2016+"	No Podcast Available
March 2, 2011	F. Jegerlehner	"What can data provide for HLbL?"	No Podcast Available
March 2, 2011	D. Moriccianni	"KLOE small angle tagger"	No Podcast Available
March 2, 2011	A. Denig	"Meson Transition Form Factors at BaBar"	No Podcast Available
March 2, 2011	H. Czyz	"EKHARA: a Monte Carlo tool for $\gamma^*-\gamma^*$ physics"	No Podcast Available
March 3, 2011	F. Jegerlehner	"Does $\rho-\gamma$ mixing solve the e^+e^- vs τ spectral function puzzle?"	No Podcast Available
March 3, 2011	K. Melnikov	"Green's functions and form factors"	No Podcast Available
March 3, 2011	W. Marciano	"Muon g-2 Comments"	No Podcast Available
March 3, 2011	E. de Rafael	"Models Discussion"	No Podcast Available
March 4, 2011	L. Roberts	"White Paper Organization"	No Podcast Available

Comparing models and ingredients

Hadronic light-by-light scattering in the muon $g - 2$: Summary

Some results for the various contributions to $a_{\mu}^{\text{LbyL;had}} \times 10^{11}$:

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	—	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	—	22 ± 5	—	15 ± 10	22 ± 5	—
scalars	-6.8 ± 2.0	—	—	—	—	-7 ± 7	-7 ± 2	—
π, K loops	-19 ± 13	-4.5 ± 8.1	—	—	—	-19 ± 19	-19 ± 13	—
π, K loops +subl. N_C	—	—	—	0 ± 10	—	—	—	—
other	—	—	—	—	—	—	—	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	—	—	—	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

- **Pseudoscalar-exchange contribution dominates numerically** (except in FGW). But other contributions are not negligible. Note **cancellation** between π, K -loops and quark loops !
- **PdRV: Do not consider dressed light quark loops as separate contribution ! Assume it is already taken into account by using short-distance constraint of MV '04 on pseudoscalar-pole contribution. Added all errors in quadrature !** Like HK(S). Too optimistic ?
- **N, JN: New evaluation of pseudoscalars.** Took over most values from BPP, except axial vectors from MV. **Added all errors linearly.** Like BPP, MV, BP, MdRR. Too pessimistic ?
- **FGW: new approach with Dyson-Schwinger equations. Is there some double-counting ?** Between their dressed quark loop (largely enhanced !) and the pseudoscalar exchanges.

Nyffeler talk @ INT

Hadronic contributions

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + \boxed{a_{\mu}^{\text{had}}} + a_{\mu}^{\text{weak}} + a_{\mu}^{??}$$

$$a_{\mu}^{\text{HVPLO}} = (692.3 \pm 4.2) \times 10^{-10}$$

$$a_{\mu}^{\text{HVPNLO}} = (-9.8 \pm 0.1) \times 10^{-10}$$

$$a_{\mu}^{\text{HLBL}} = (10.5 \pm 2.6) \times 10^{-10}$$

$$a_{\mu}^{\text{had}} = (693.0 \pm 4.9) \times 10^{-10}$$

$$a_{\mu}^{\text{exp}} = 0.00\,116\,59\boxed{2\,0}89(63)$$

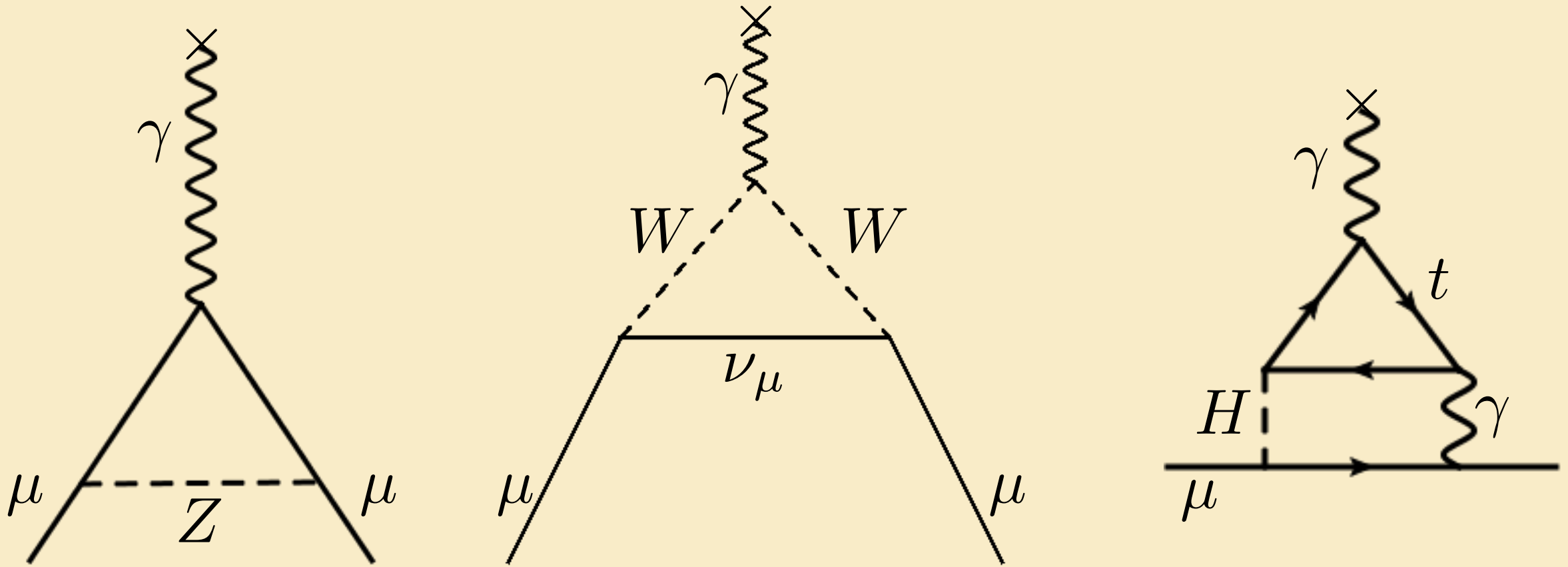
$$a_{\mu}^{\text{had}} = 0.00\,000\,00\boxed{6\,9}30(49)$$

Shows up in eighth decimal place.

Electroweak contributions

$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{had}} + a_{\mu}^{\text{weak}} + a_{\mu}^{\text{???}}$$

Unambiguously calculable - BNL experiment sensitive



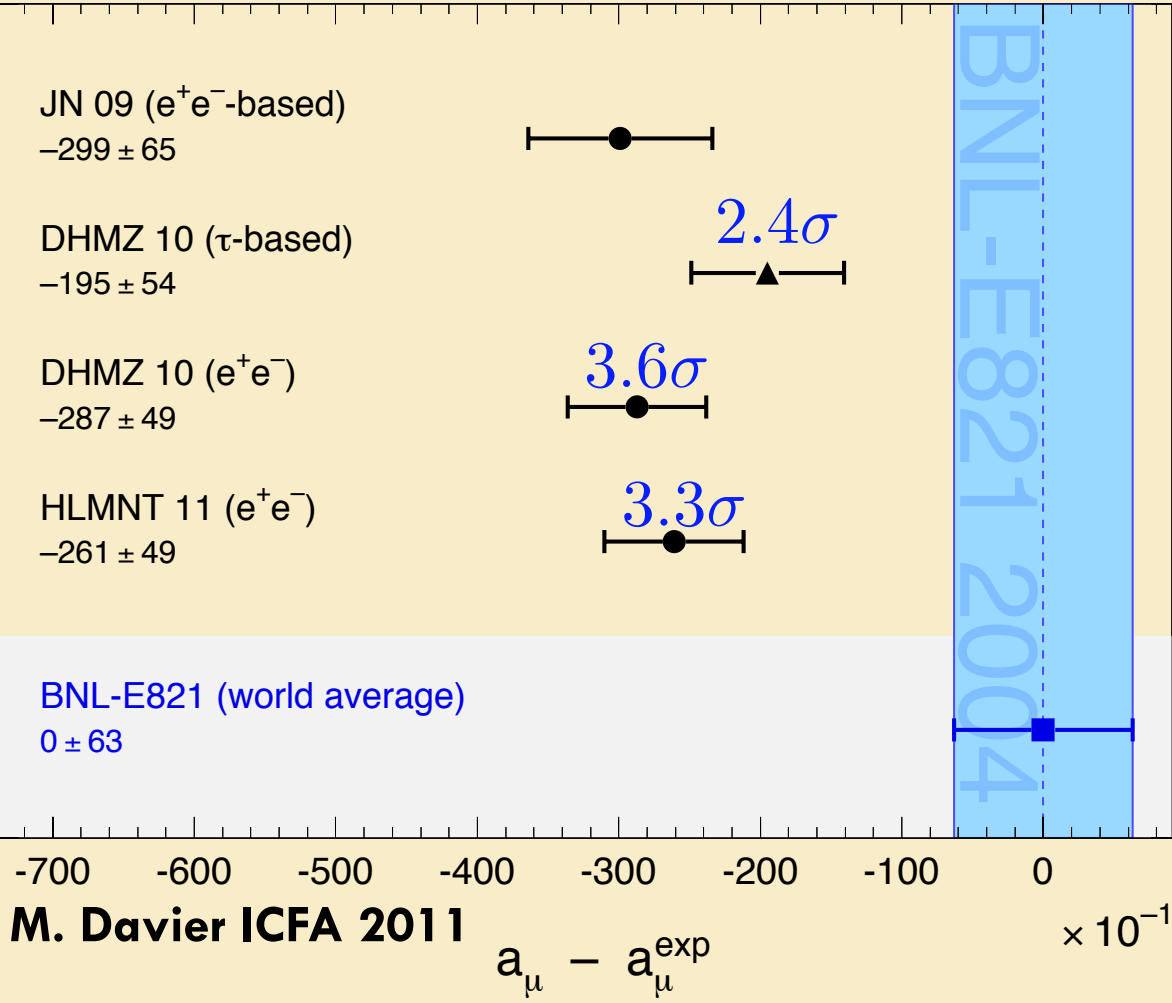
$$a_{\mu}^{\text{exp}} = 0.00\,116\,592\,089(63)$$

$$a_{\mu}^{\text{EW}} = 0.00\,000\,000\,154(2)$$

Shows up in tenth decimal place

Standard Model Prediction

Status: summer 2011 (published results shown only)



$$a_\mu^{\text{QED}} = 0.00\,116\,584\,718\,09(15)$$

$$a_\mu^{\text{had}} = 0.00\,000\,006\,930(49)$$

$$a_\mu^{\text{EW}} = 0.00\,000\,000\,154(2)$$

$$a_\mu^{\text{SM}} = 0.00\,116\,591\,802(49)$$

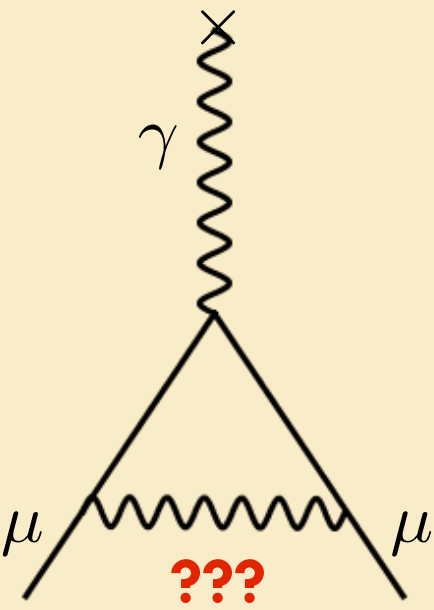
$$a_\mu^{\text{exp}} = 0.00\,116\,592\,089(63)$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287(80) \times 10^{-11}$$

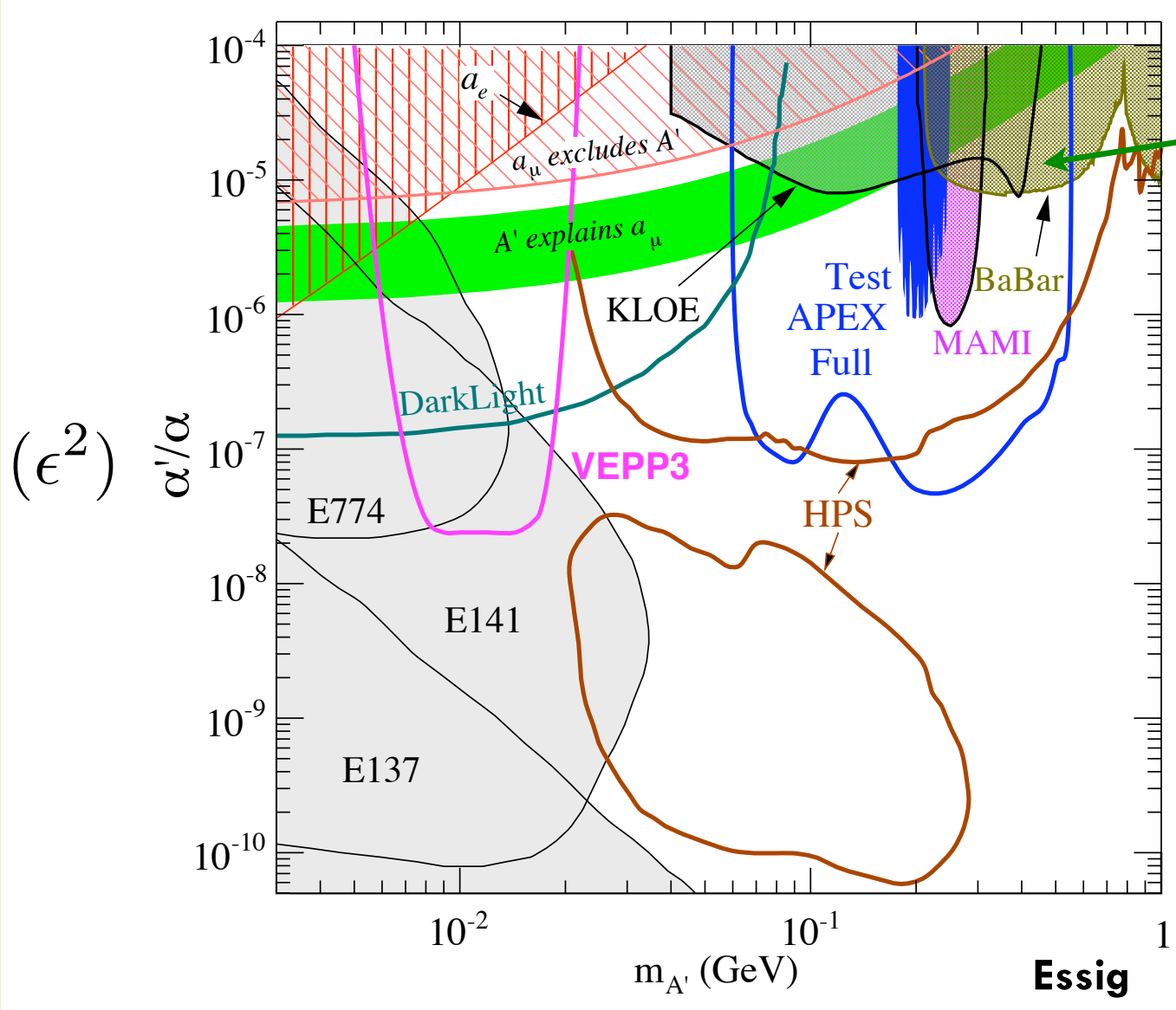
$$> 3\sigma$$

New Physics?

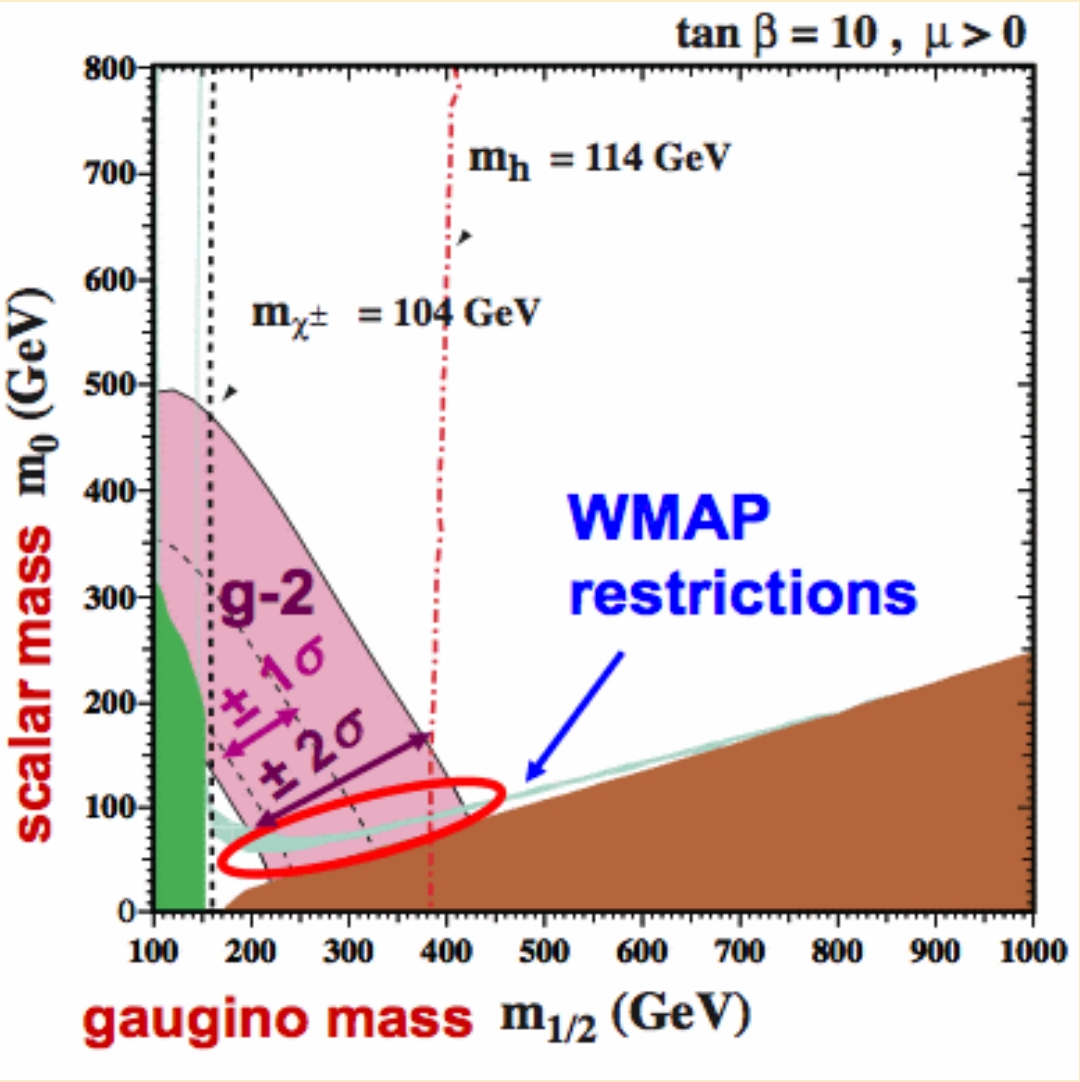
$$a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{had}} + a_{\mu}^{\text{weak}} + \boxed{a_{\mu}^{???}}$$



Dark Photons?



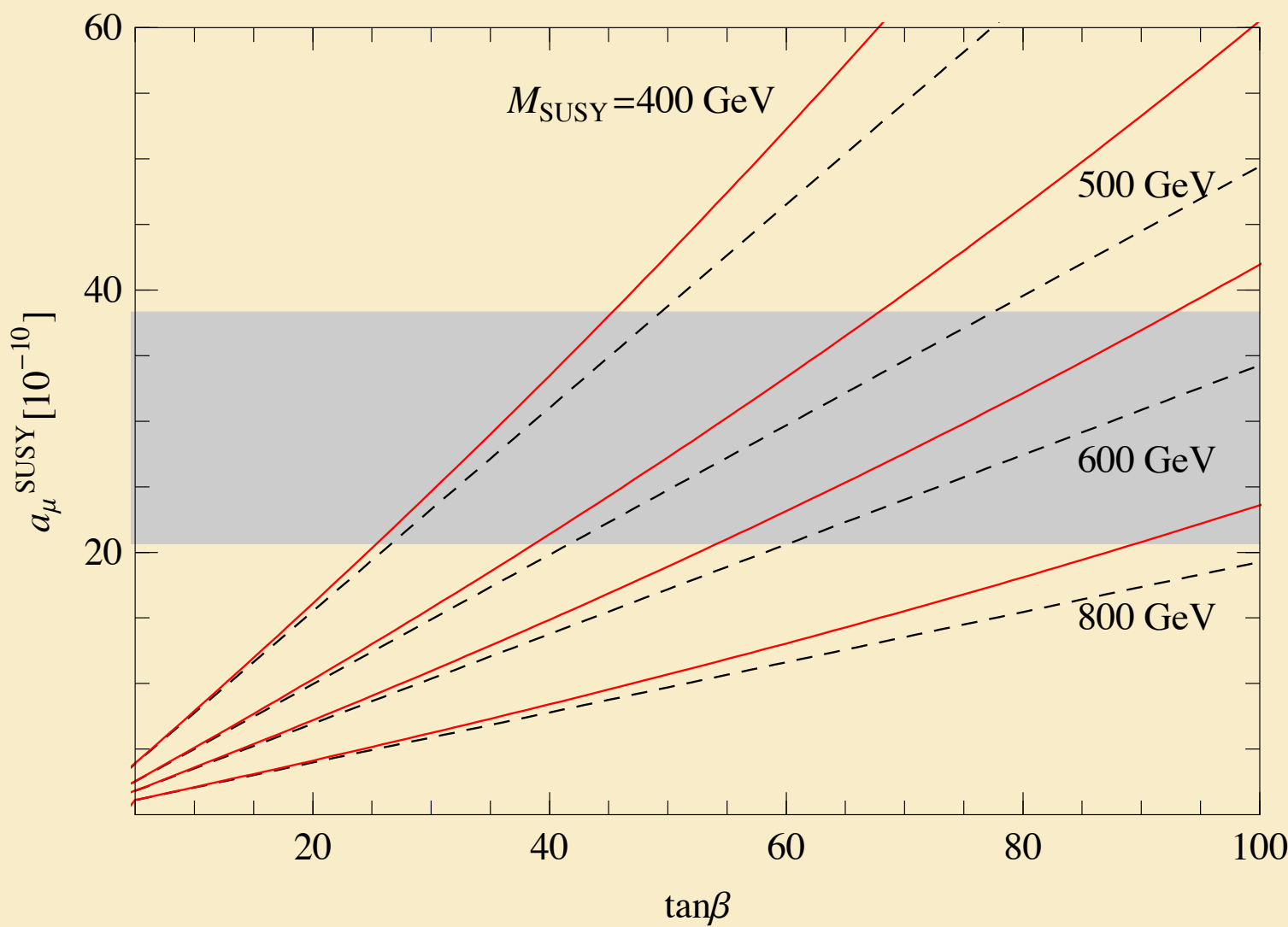
SUSY?



SUSY?

**SUSY with mass scale of
several 100 GeV is consistent
with discrepancy**

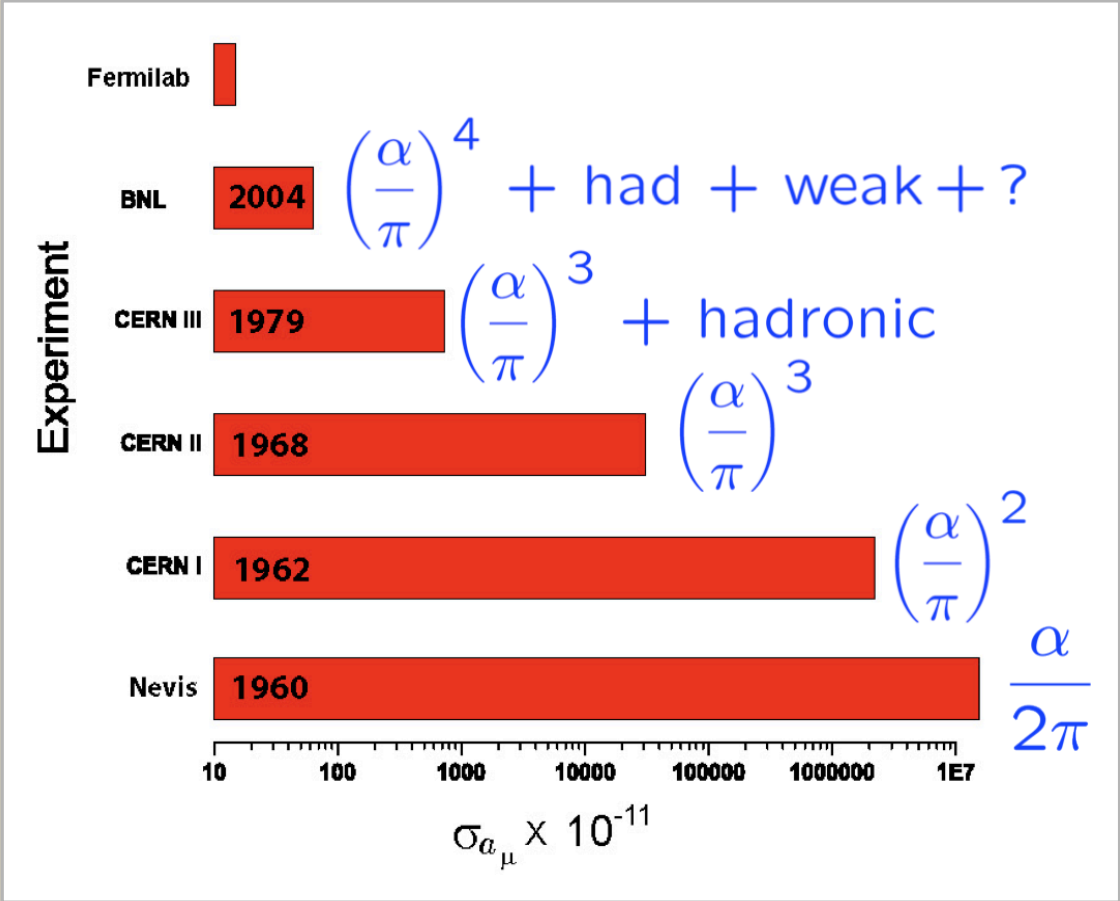
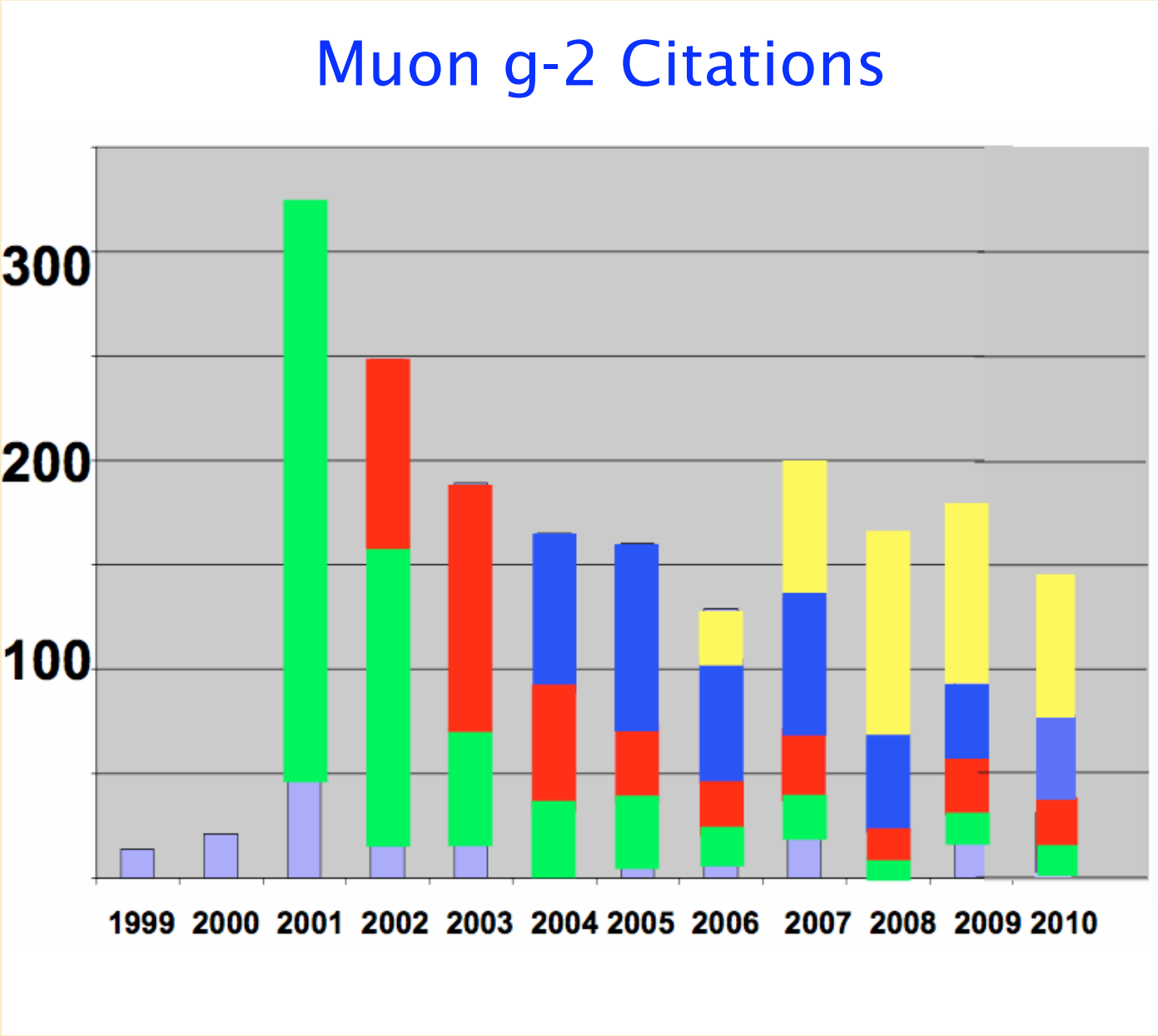
$$a_{\mu}^{\text{SUSY}} \approx 13 \times 10^{-10} \text{sign}(\mu) \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \tan \beta$$



Grey bar is BNL discrepancy
Red lines include a calculated enhancement from 2 loop corrections
g-2 likes tan beta ~ 40

Summary of present status

Precision of results has generated enormous interest



Different colors are different E829 publications

Explore the discrepancy with a next experiment

~ 3σ discrepancy - a hint of something new?

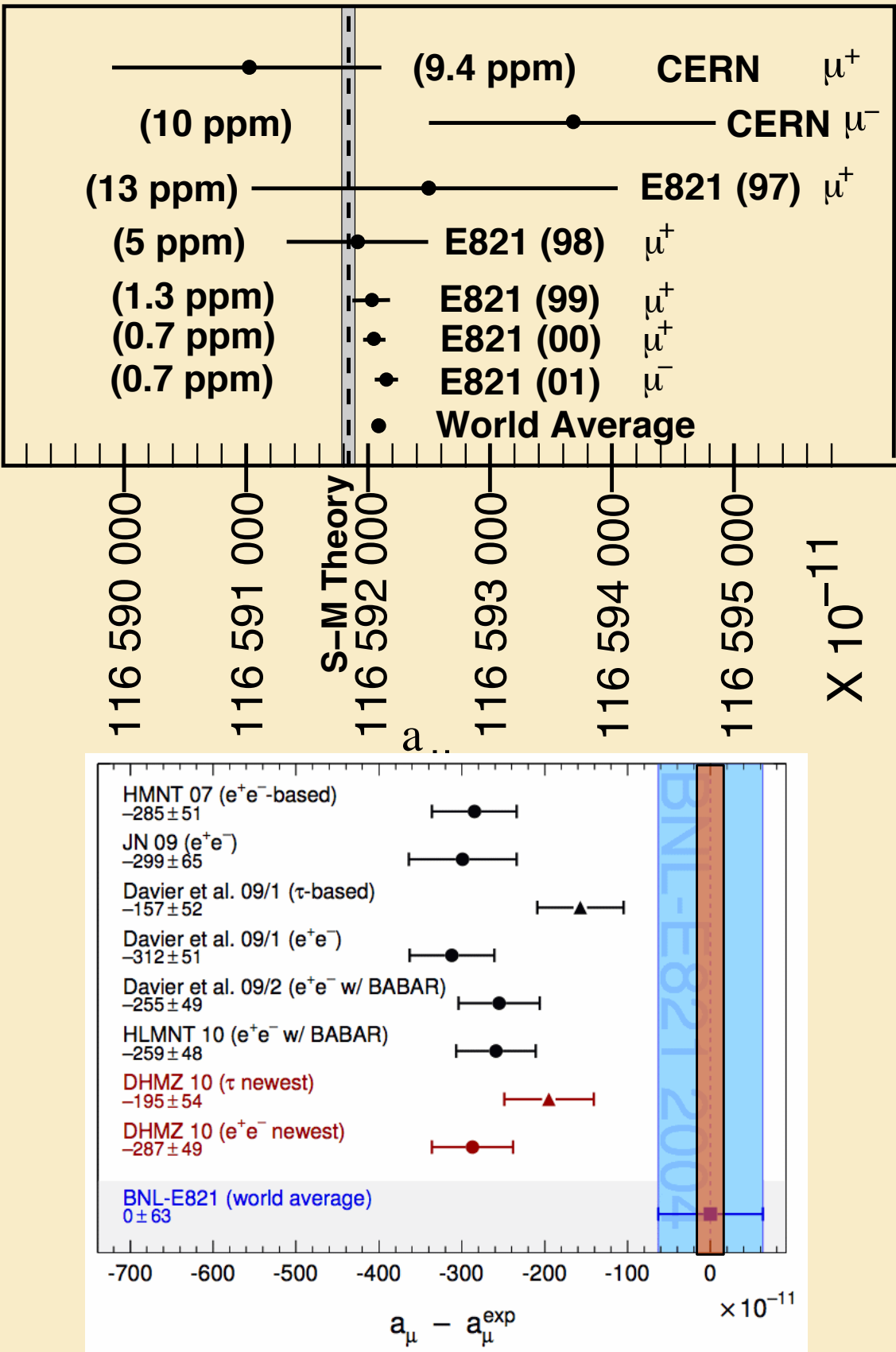
Time for another experiment!

Goal: a_μ to $\pm 16 \times 10^{-11}$ (0.14 ppm)

0.10 ppm stat, 0.07 ppm systematic on both ω_a and ω_p

With a 0.14 ppm measurement, current discrepancy becomes 5.6σ (7.5σ if theory drops to 0.3 ppm)

What can you do with a factor of 4 better experimental result?

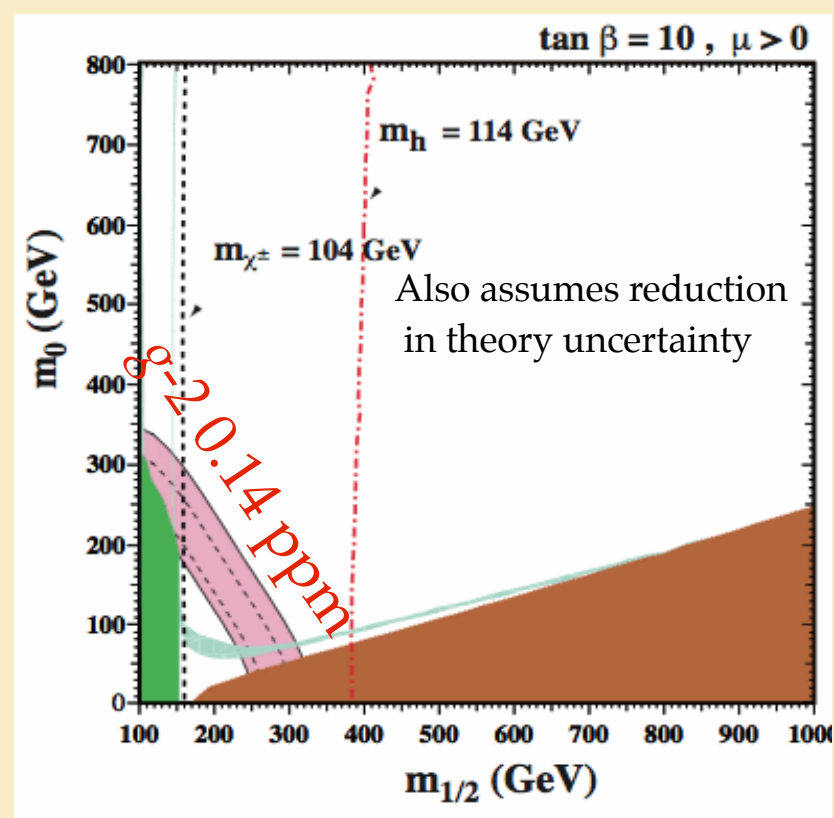
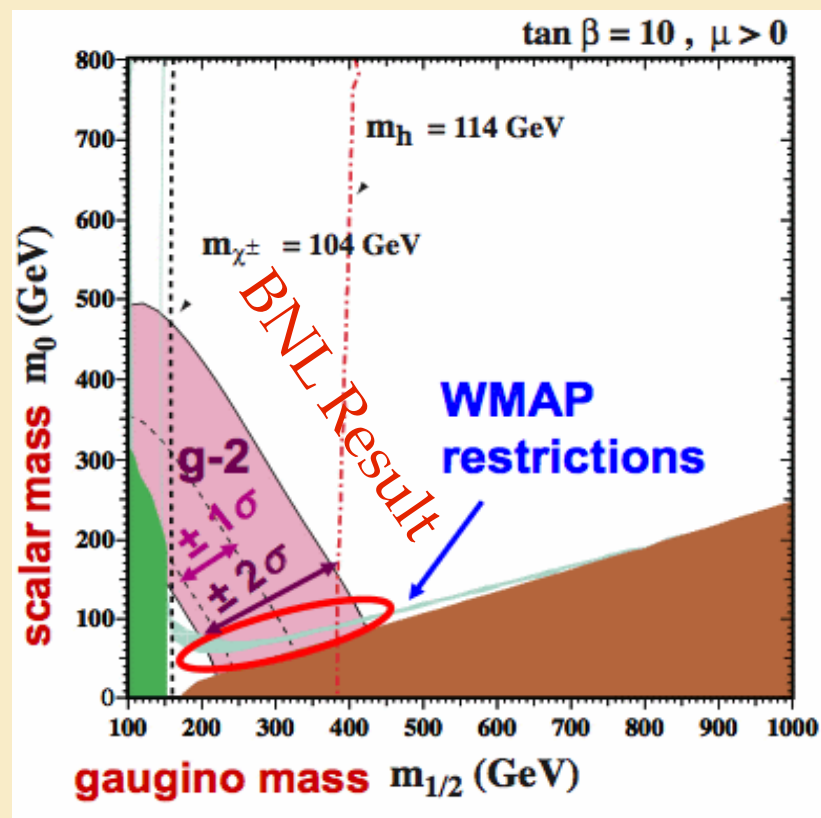
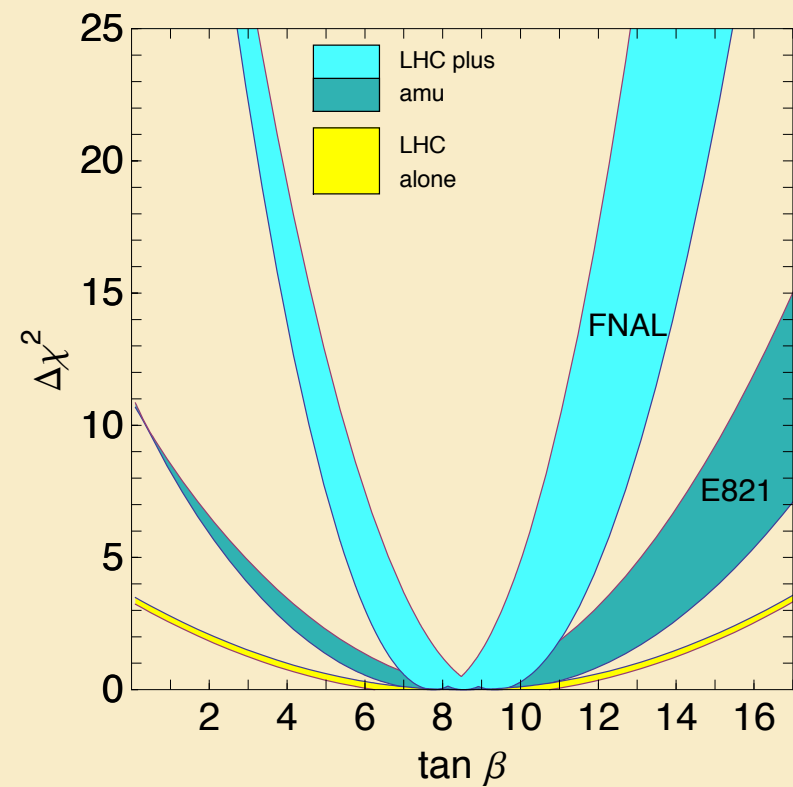
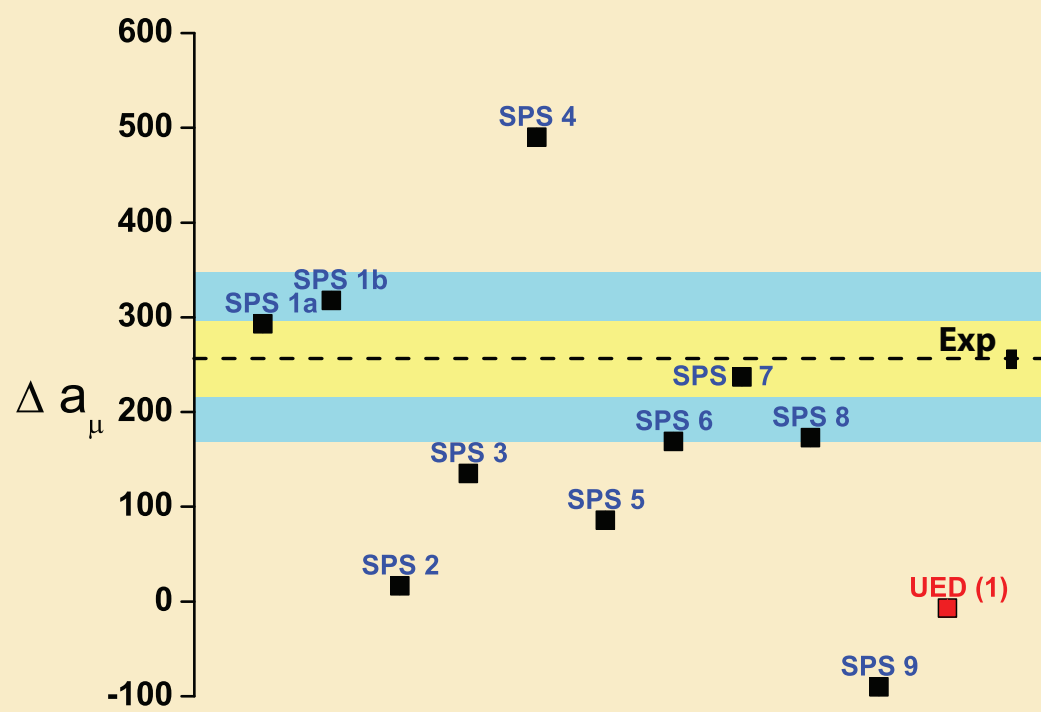


M. Davier

Most of what counts is on the low end!!

New physics with 0.14 ppm

Complementary to LHC



Lyon - New g-2 - ANL - 2012-01

55

Upper right plot uses SPS1a* (same as SPS1a but with $\tan \beta = 8.5$) – assume LHC finds all of the susy particles that it can. But it can't do $\tan \beta$ very well. Curves are from a global fit that includes various Δa_μ

Bottom plots are CMSSM $\tan \beta = 10$, $A_0=0$, $\text{sign } \mu+$

SPS points are at <http://www.ippp.dur.ac.uk/~georg/sps/sps.html>
 SPS1a is $\mu > 0$, $\tan \beta = 10$, $M_0=100$, $M_{1/2}=200$, $A = 400$

New g-2 experiment justification

**Discrepancy with SM and complementarity with LHC makes for easy physics motivation. If there is new physics,
LHC + g-2 will be a powerful combination**

BNL E821 was statistics limited

Factor of 4 is about the limit of the current apparatus

Need 21x statistics to achieve this goal !!!

Gotta get more beam! Move to Fermilab -- Literally!

Movin' Out – Transporting the Ring

The existing BNL storage ring makes the new experiment work
Three ~50' diameter coils are continuously wound!
The long trip is easy - Barge it

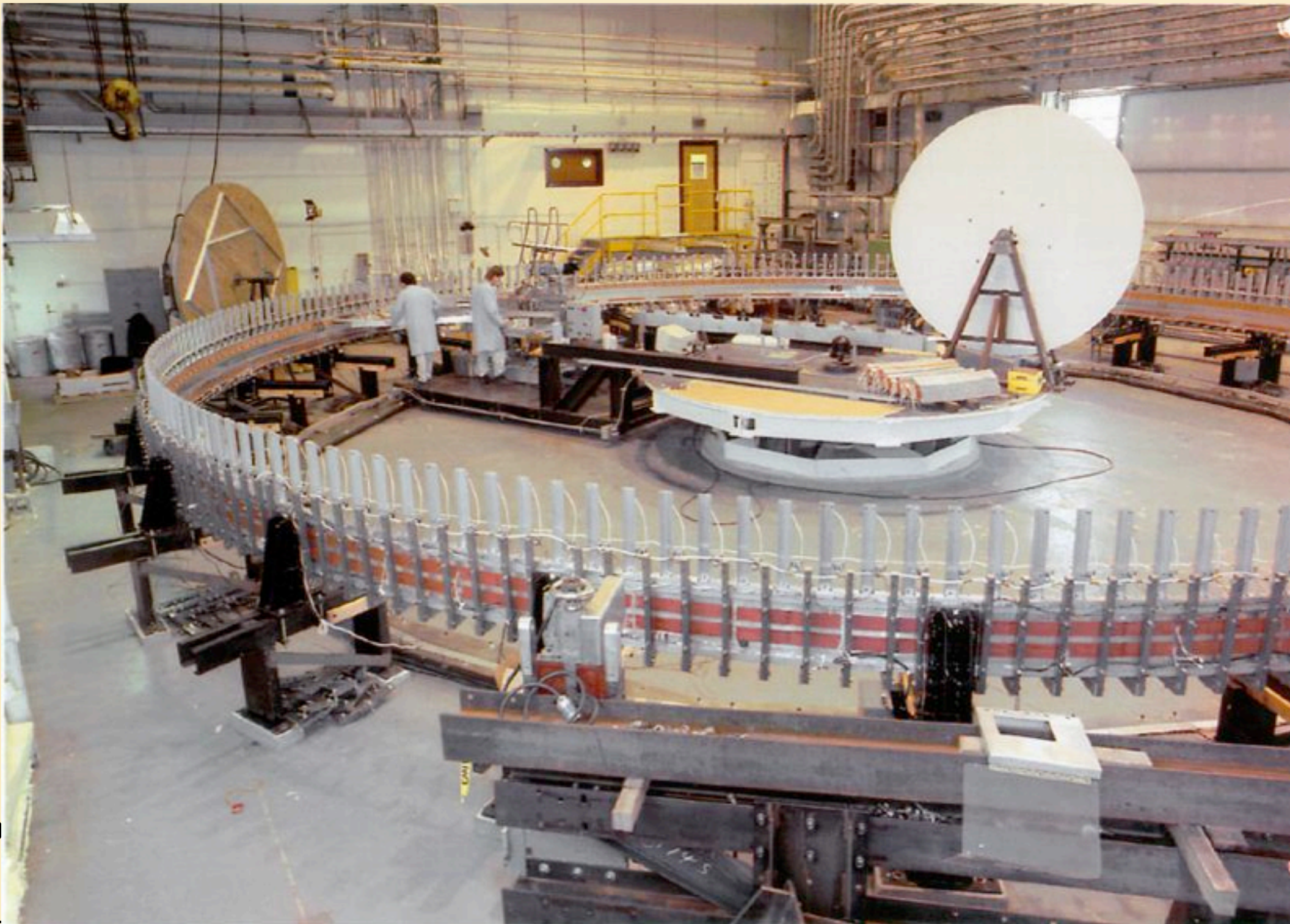


About a month long trip. Ring ends up in Lemont

Movin' Out – Transporting the Ring

The existing BNL storage ring makes the new experiment work
Three ~50' diameter coils are continuously wound!

The



Abo

Lyon - New g-2 - ANL - 2012-01

Movin' Out – Transporting the Ring

The existing BNL storage ring makes the new experiment work
Three ~50' diameter coils are continuously wound!
The long trip is easy - Barge it



About a month long trip. Ring ends up in Lemont

The getting to and from the barge is hard

Inner cryostats are 3.5T ea

Outer cryostat is 8.5T

Connections < 5T

Existing shipping frame is 6T

Way Cool Helicopter (Skycrane):

Max load 12.5T

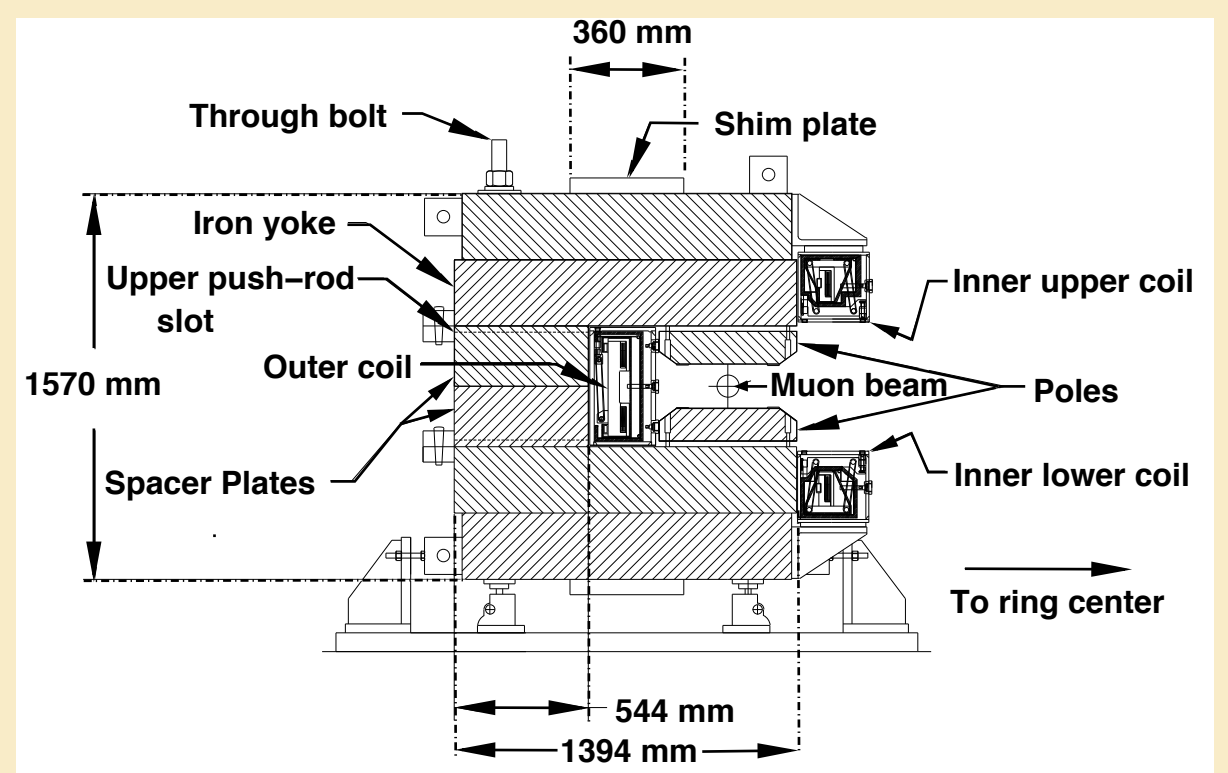
Need sterile 300 ft field
underneath if jettison-able

Maybe bolt to helicopter?

Boring Truck:

Carry entire package at once

Ring to go horizontal and vertical



The getting to and from the barge is hard

Inner cryostats are 3.5T ea

Outer cryostat is 8.5T

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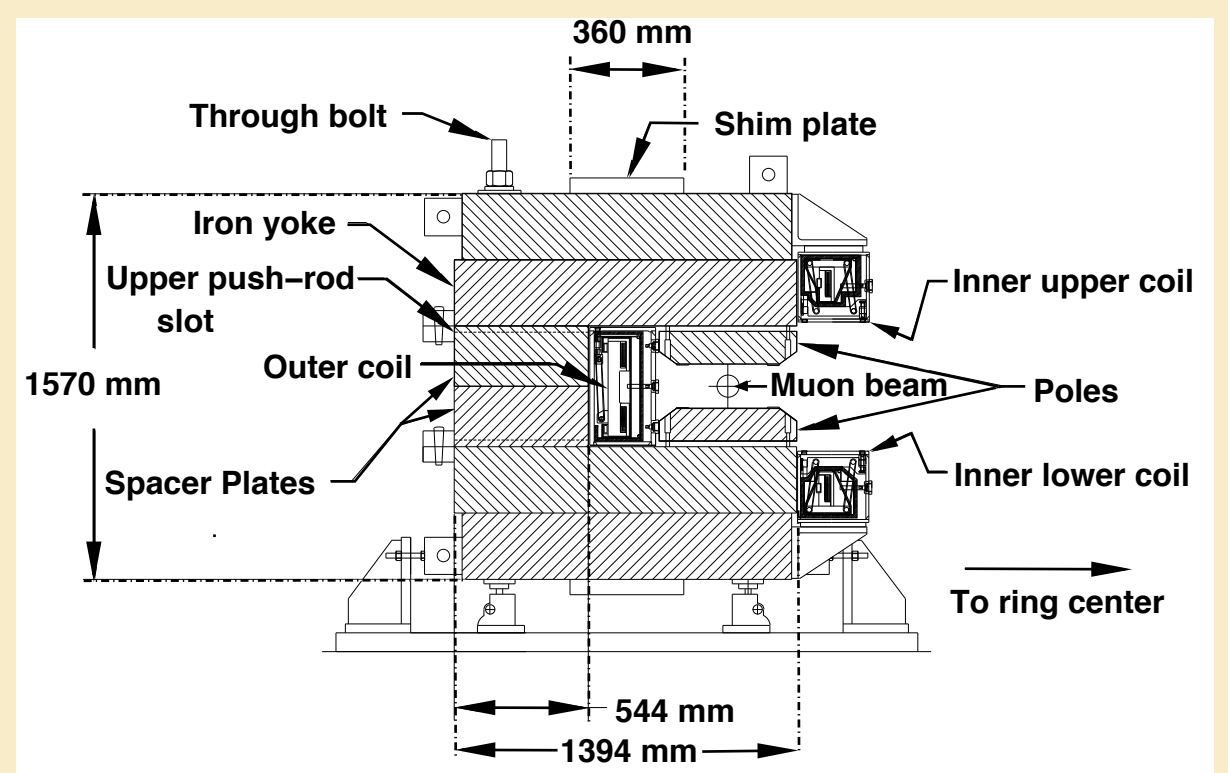
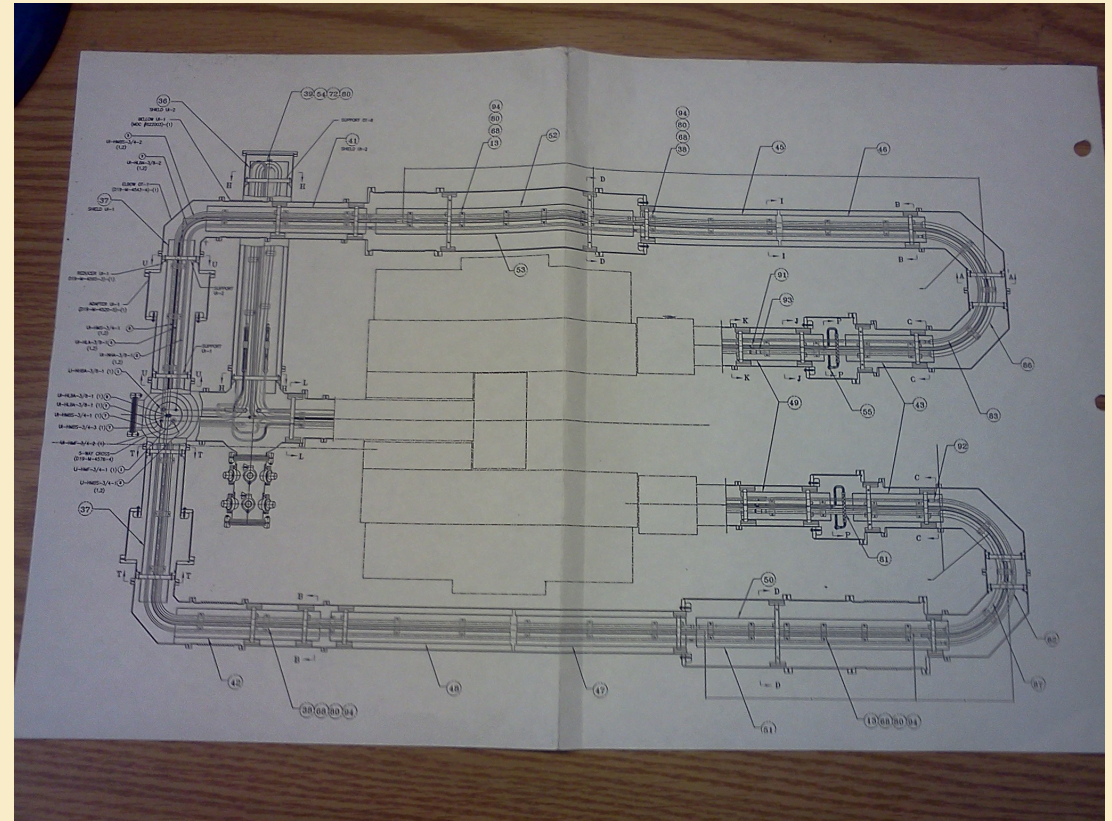
Need sterile 300 ft field underneath if jettison-able

Maybe bolt to helicopter?

Boring Truck:

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Ring to go horizontal and vertical



The getting to and from the barge is hard

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Carry entire package at once
Ring to go horizontal and vertical



Got the Coil on a String!

In April 1992, as the Bulletin reported, the world's largest superconducting coil "on a string" was hanging not from a finger but from a massive crane outside Bldg. 919. Three coils had been constructed inside the building. The third and largest coil was pulled on special heavy-duty tracks past a removable wall to the outdoors, attached to the crane, then lowered into its final position on the foundation that held the two previously completed inner coils within the building. Work then continued to ready the experiment for the storage ring's commissioning scheduled for December 1993.

The getting to and from the barge is hard

Inner cryostats are 3.5T ea

Outer cryostat is 8.5T

Connections < 5T

Existing shipping frame is 6T

Way Cool Helicopter (Skycrane):

Max load 12.5T

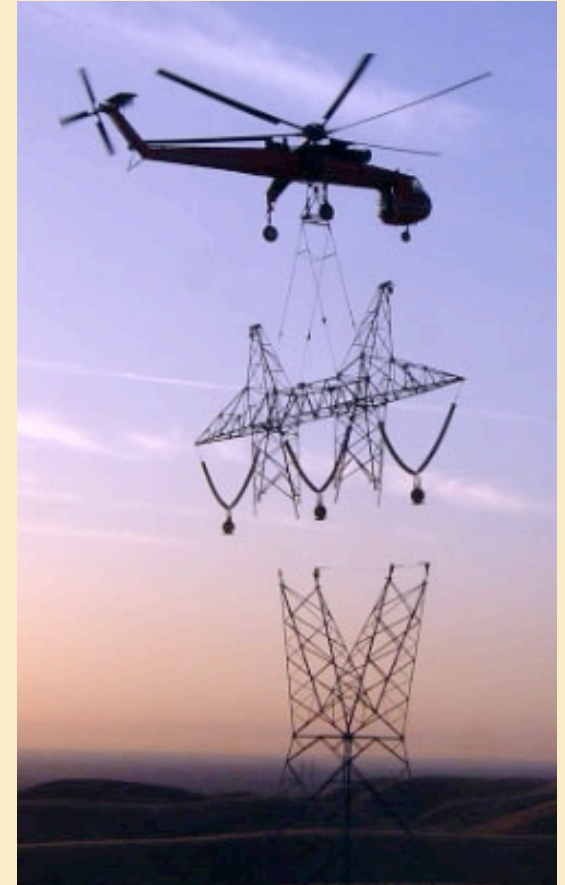
**Need sterile 300 ft field
underneath if jettison-able**

Maybe bolt to helicopter?

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Carry entire package at once

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underneath if jettison-able**

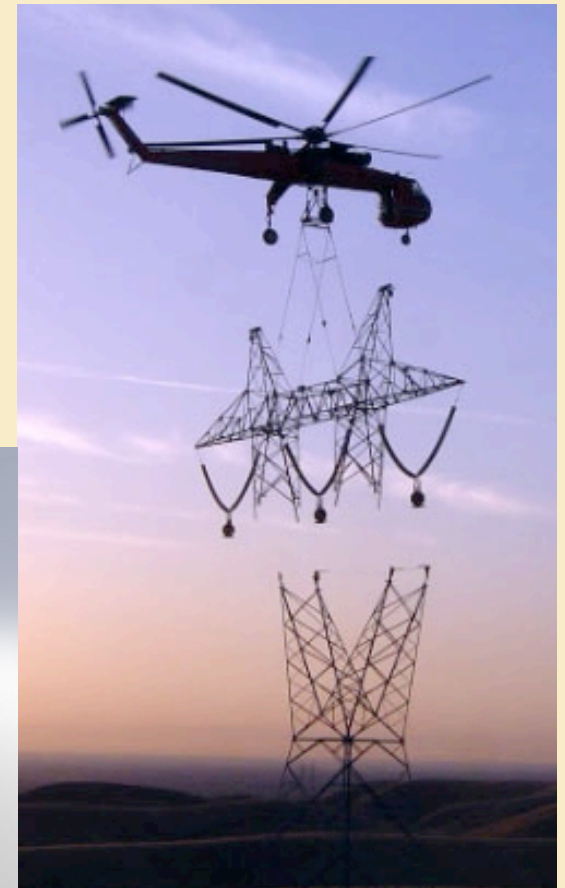
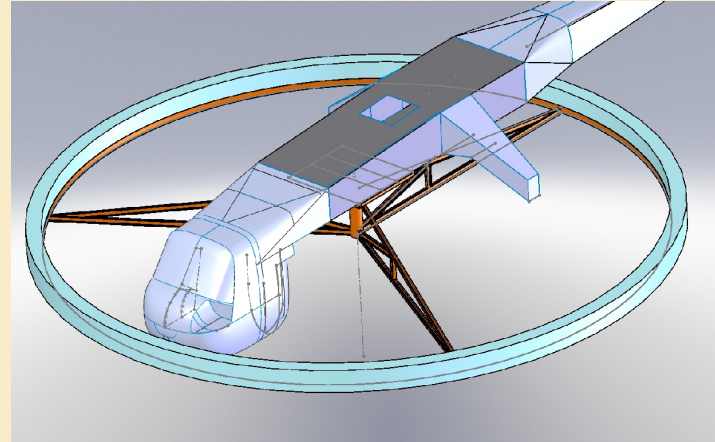
Maybe bolt to helicopter?

Boring Truck:

Carry entire package at once

Ring to go horizontal and vertical

Courtesy Erickson



The getting to and from the barge is hard

Inner cryostats are 3.5T ea

Outer cryostat is 8.5T

Connections < 5T

Existing shipping frame is 6T

Way Cool Helicopter (Skycrane):

Max load 12.5T

Need sterile 300 ft field underneath if jettison-able

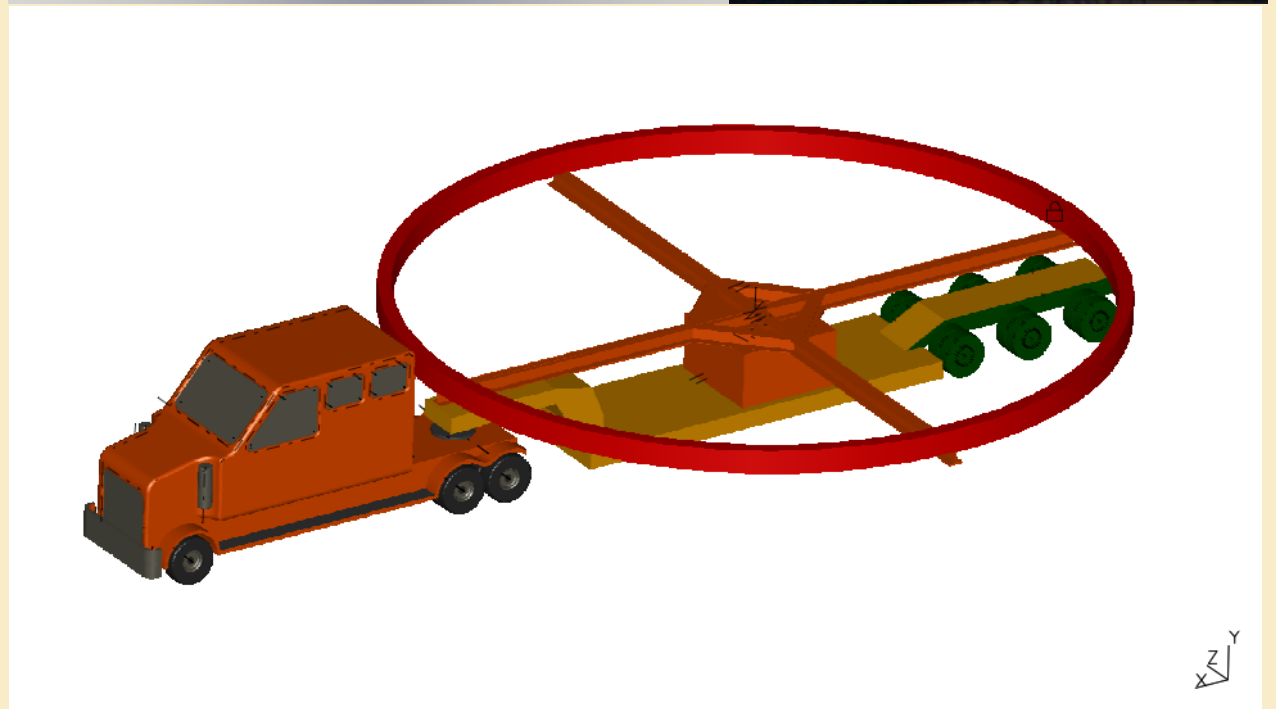
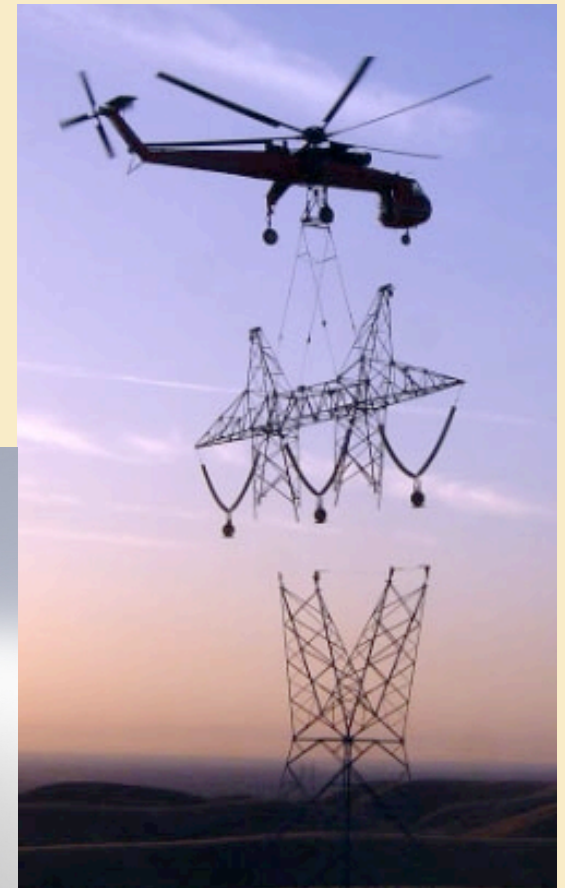
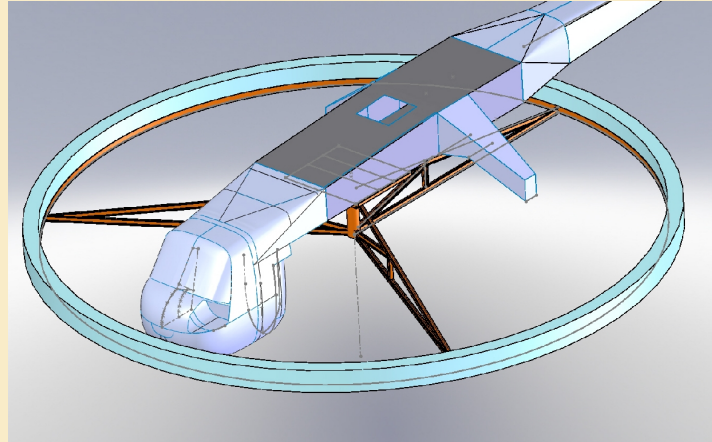
Maybe bolt to helicopter?

Boring Truck:

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Ring to go horizontal and vertical

Courtesy Erickson



We've started disassembly already

Summer 2011 at Brookhaven



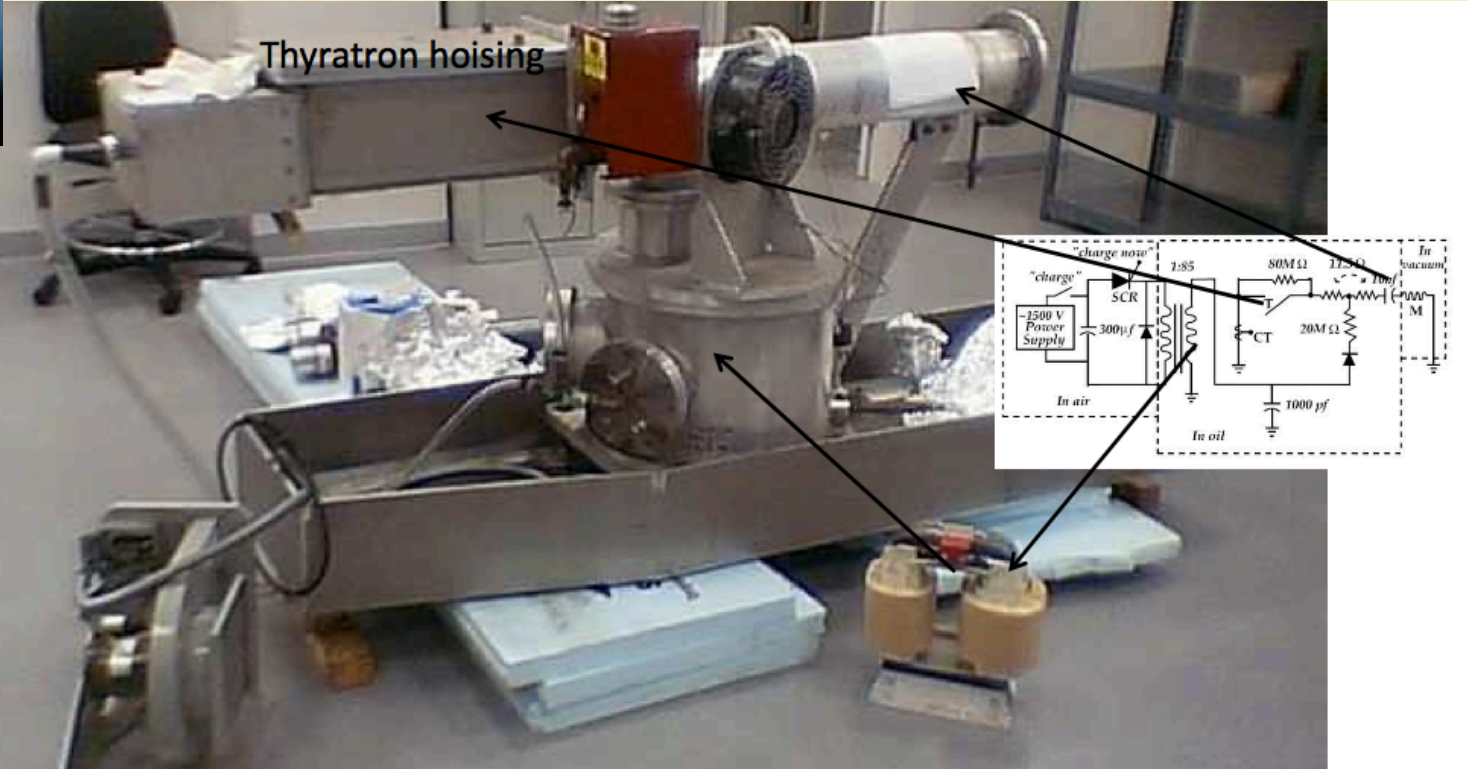
Lyon - New g-2 - ANL - 2012-01

And studying old parts

Cornell got this box of stuff



And reconstructed a kicker



A better beam from Fermilab

Need 180B positron decays
With 4×10^{20} Protons on target in 2 year run,
need to improve μ/p by factor of 6 (11 to be safe)

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx 2.7\text{E-}5$	$\approx 1.1\text{E-}5$	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi/p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflexor	closed end	open end	2
total			11.5

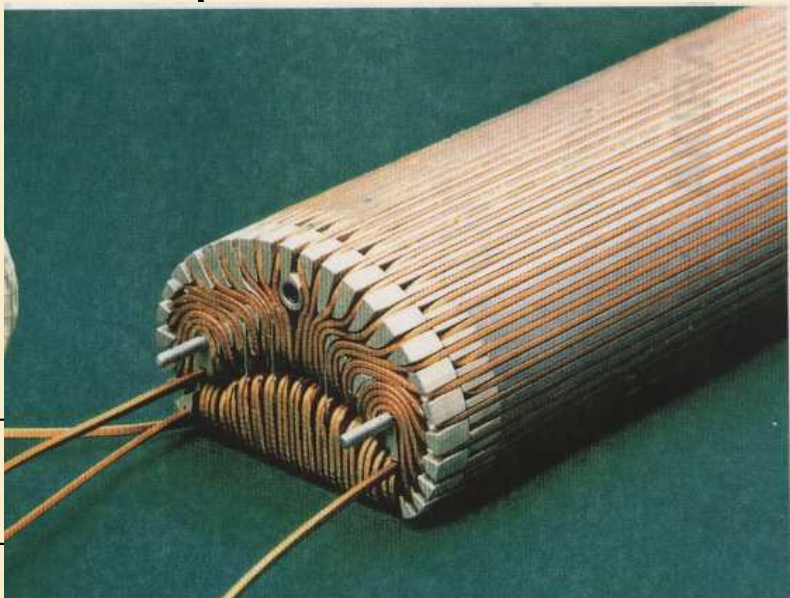
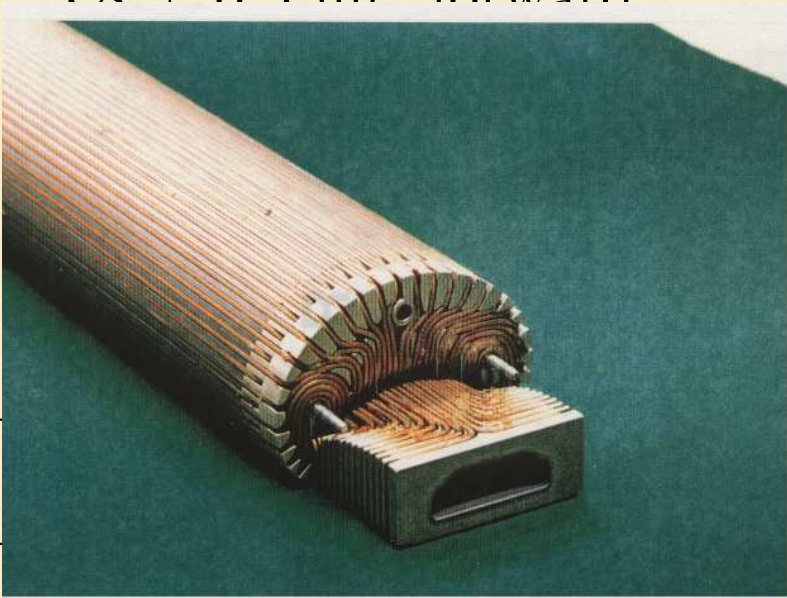
Note that we start at a loss since 24 GeV vs 8 GeV
 Y_π is pion yield
18 Hz storage ring fills

Both closed and open prototypes were built, but only closed was built to full scale because it was thought to be easier. Closed had smaller easier to shield fringe field. But multiple scattering and energy loss cost a factor of two. Already know how to build open end at full scale. Cancel leakage field by a passive superconducting sheet.

A better beam from Fermilab

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$\delta p_\pi/p_\pi$ pion momentum band			
FODO lattice spacing			
inflexor			
total			



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Ypi is pion yield
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Synergies between g-2 and Mu2e

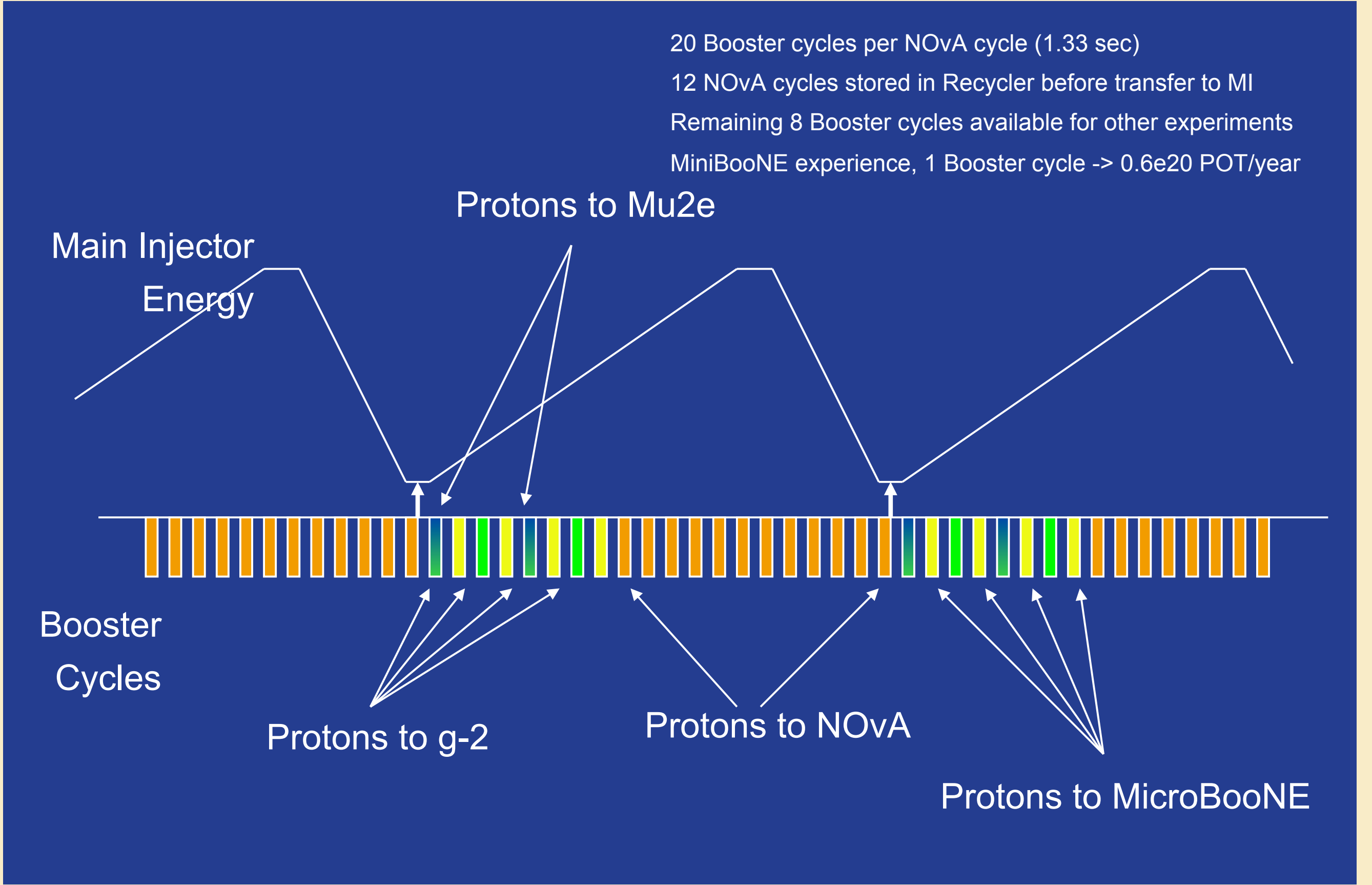
Proton Improvement Plan (PIP)

- Currently Booster limited by RF system to <9 Hz operation
- Proton Improvement Plan will allow 15 Hz operation of the Booster
- NOvA needs 9 Hz, leaving 5e20 POT/yr available for other programs
 - MicroBooNE (2014) – up to 6 Hz
 - g-2 (2016) – 3 Hz
 - Mu2e (2019) – 1.5 Hz

Experiment	Total Beam Request	Available Protons/year	Time Needed
MicroBooNE*	6.7 e20	Up to 5.0 e20	< 3 years
Muon g-2	4.0 e20	2.4 e20	2 years
Mu2e	3.6 e20	1.2 e20	3 years

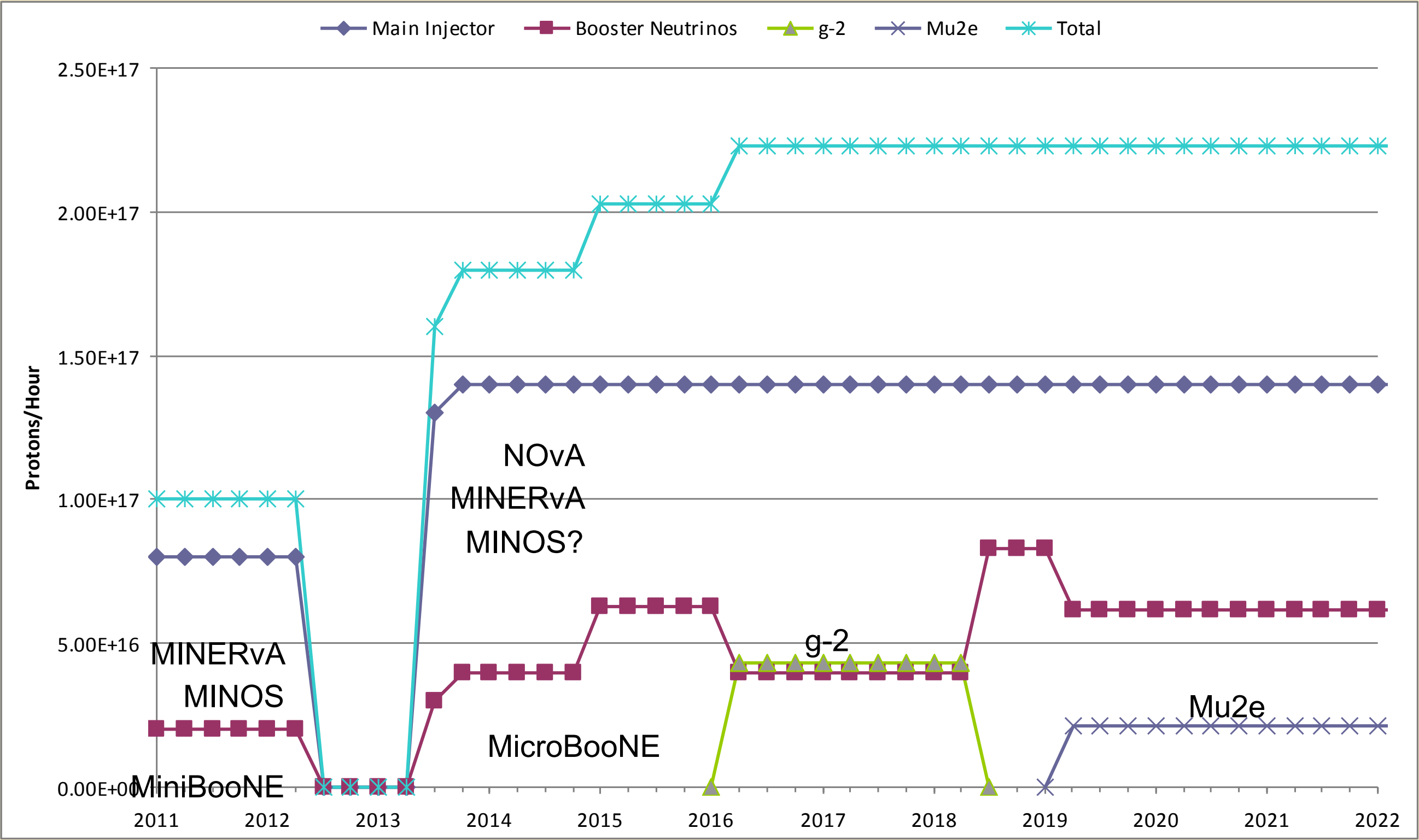
* MicroBooNE can run in parallel with g-2 or Mu2e, but g-2 and Mu2e have to run separately

Booster beam structure

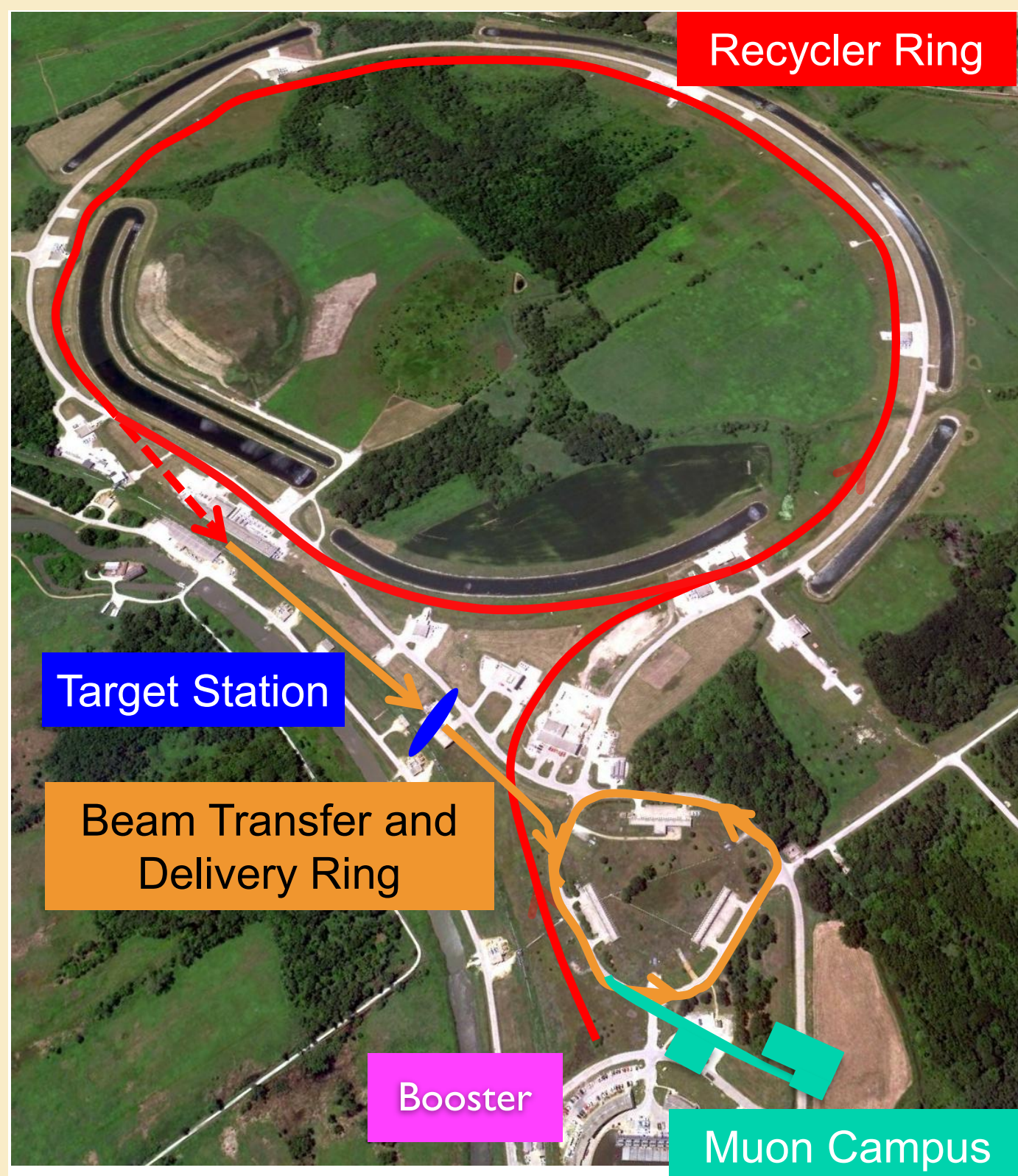


There are 20 Booster “batches” per Main Ring cycle

Who gets beam when?



Beam delivery to g-2



- **Recycler**
 - 8 GeV protons from Booster
 - Re-bunched in Recycler
 - New connection from Recycler to P1 line (existing connection is from Main Injector)
- **Target station**
 - Target
 - Focusing (lens)
 - Selection of magic momentum
- **Beamlines / Delivery Ring**
 - P1 to P2 to M1 line to target
 - Target to M2 to M3 to Delivery Ring
 - Proton removal
 - Extraction line (M4) to g-2 stub to ring in MC1 building

8 GeV From Booster – Long train of 84 53 MHz proton bunches reformed into 4 bunches of 2.5 MHz
Each bunch kicked out every 8–12 ms
100ns bunches
Note the new names!!
Target is inconel (mostly nickel with some chromium and other stuff)
Long 900m decay line for pions
Go around “delivery ring” 3–4 times, kick out protons
Much improved hadron flash

A huge recycling project



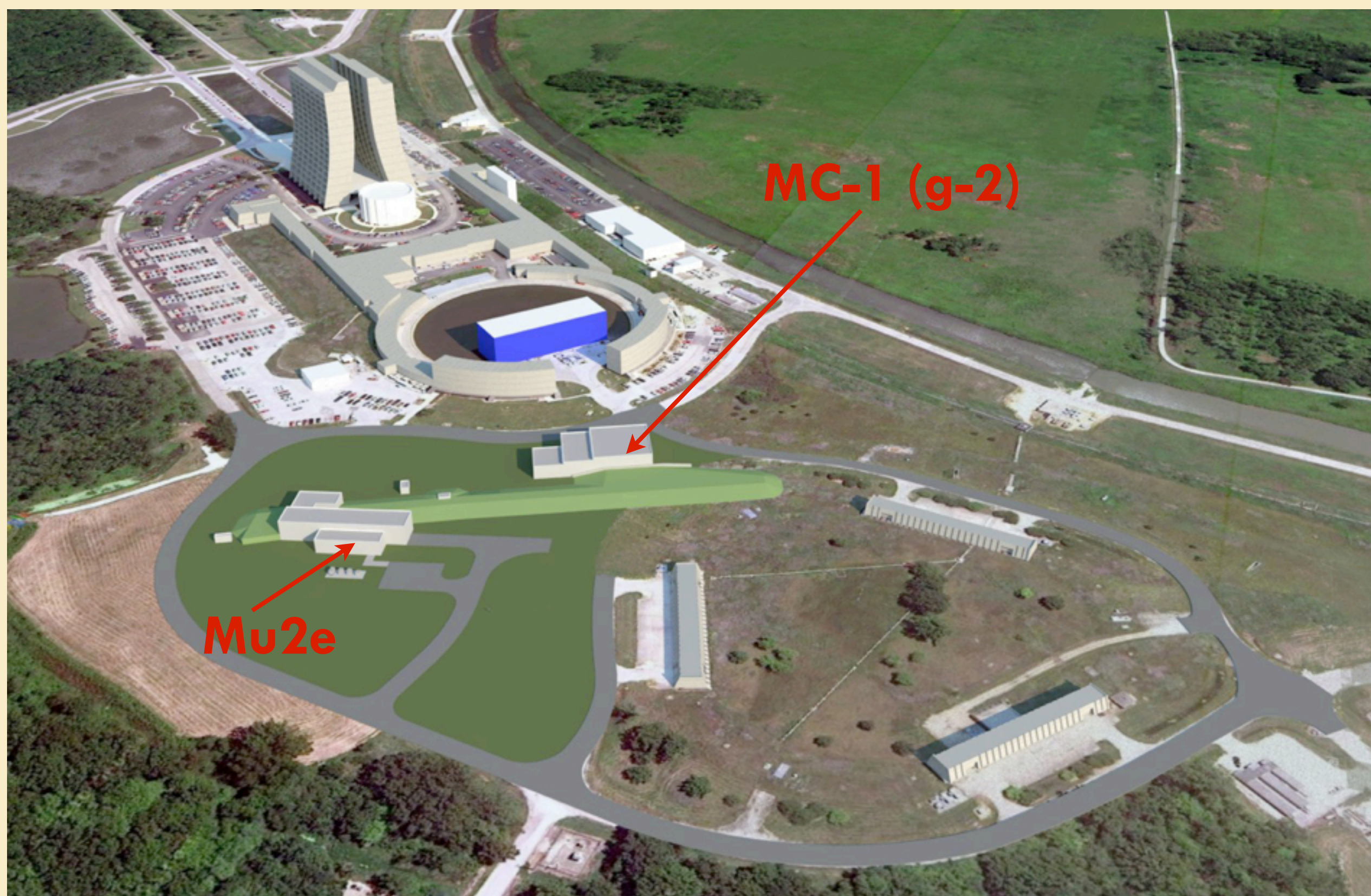
Make excellent use of existing Tevatron infrastructure

Beam line from BNL



- g-2 ring
- g-2 beamline
- Debuncher Ring
- Magnets, pumps, stands and other Accumulator Ring components
- AP transfer lines
- AP-0 Target Station
- AP-2 beamline magnets
- Main Injector RF ferrites
- Tevatron satellite refrigerators
- Tevatron N₂ and He storage tanks
- Tevatron cryo line
- Tevatron High Temperature Superconducting leads
- Tevatron vacuum equipment
- Tevatron loss monitors
- Tevatron BPM electronics
- Tevatron electronics crates
- Tevatron control cards
- Tevatron damper system
- Misc. Tevatron Instrumentation
- Shielding steel
- Transformers

The Fermilab Muon Campus



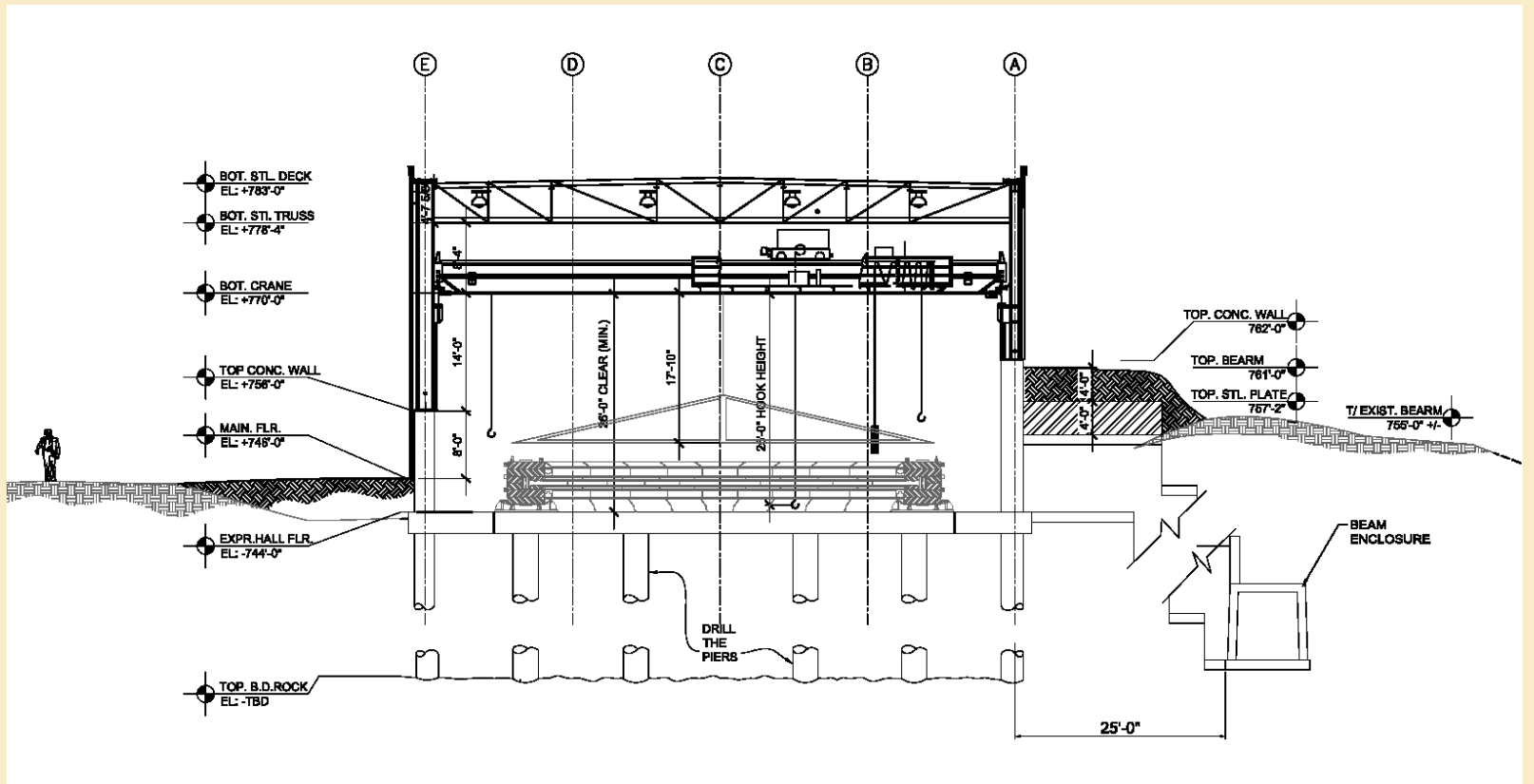
MC-1 Building for g-2



High bay 80' x 80' for ring

Medium bay 40' x 70' for power supplies for g-2, beam, Mu2e AC dipole and HVAC

**Low bay 40' x 40' for
cryo plant for both
experiments**

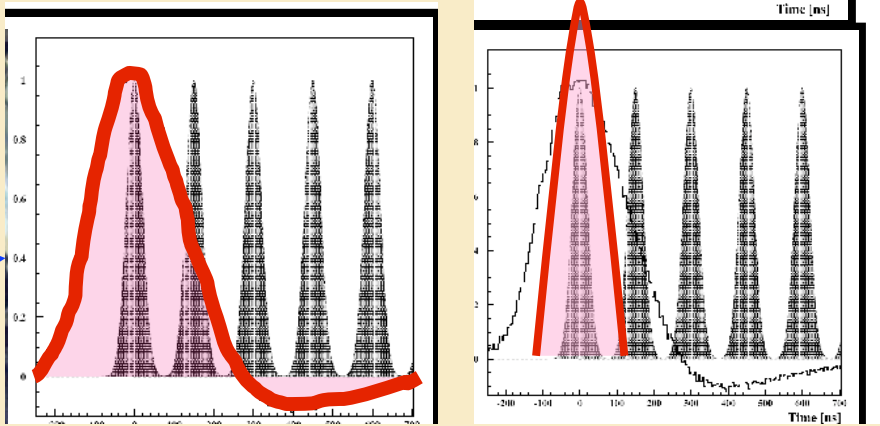


Fully temperature controlled
Close to Booster - may need magnetic shielding

Improving ω_a

E821 Error	Size	Plan for the New $g-2$ Experiment	Goal
	[ppm]		[ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

- + No hadronic flash, better laser calibration
- + New hodoscopes, tracking, open inflector, scraping
- + Segmented calorimeters
- + Improved kickers

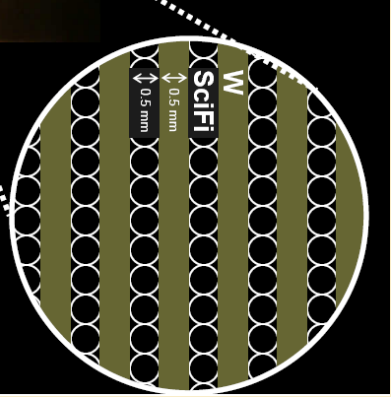
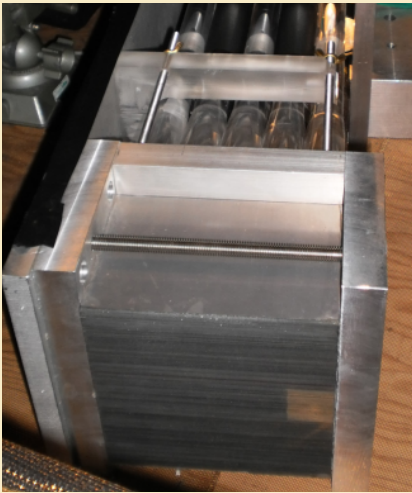


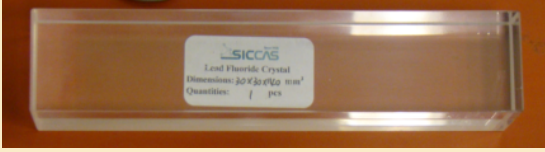
Lyon - New $g-2$ - ANL - 2012-01

Gain changes from early to late 0.15%

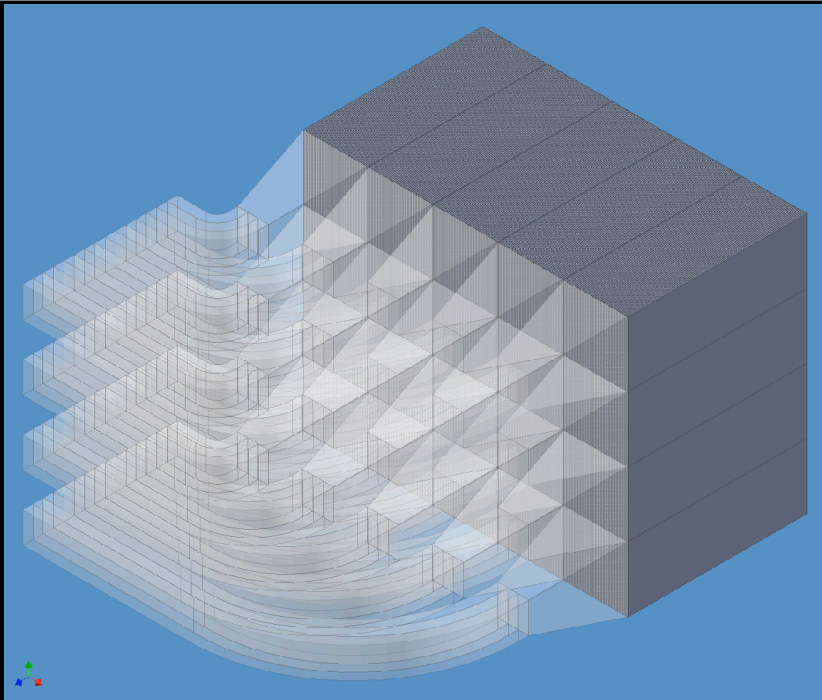
Segmented calorimeters

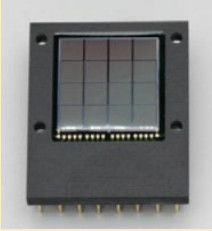

For reduced pileup

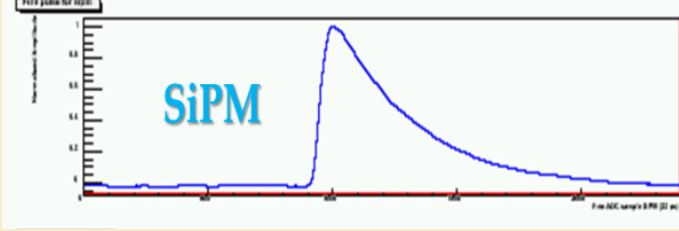
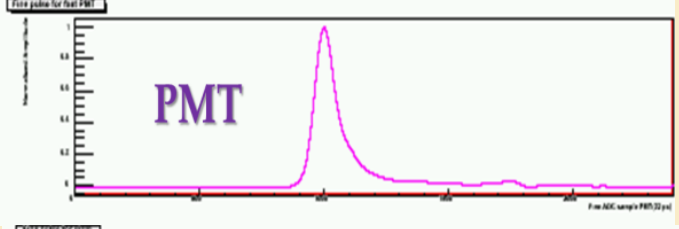




**W/SciFi or PbF₂
Cherenkov?**





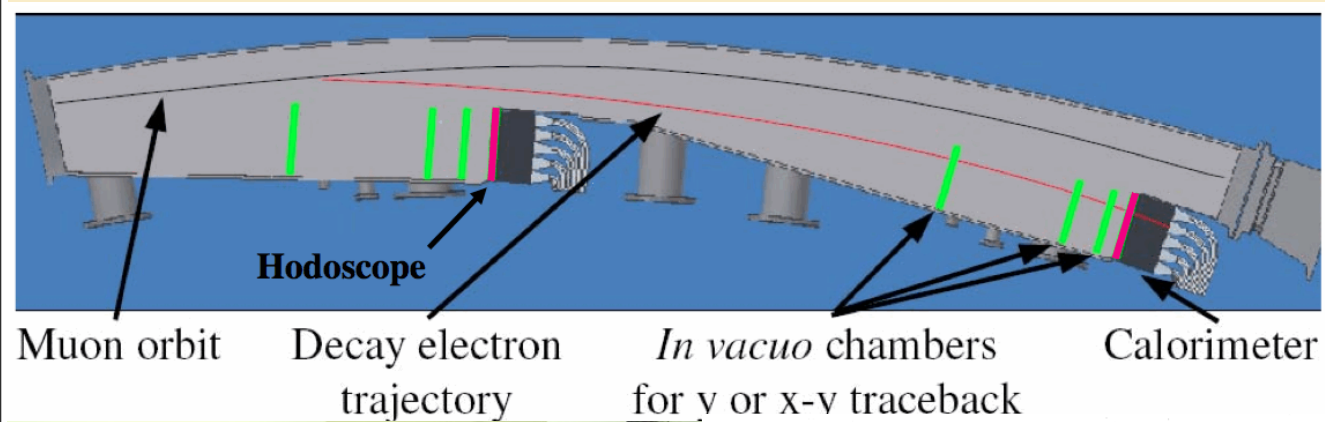
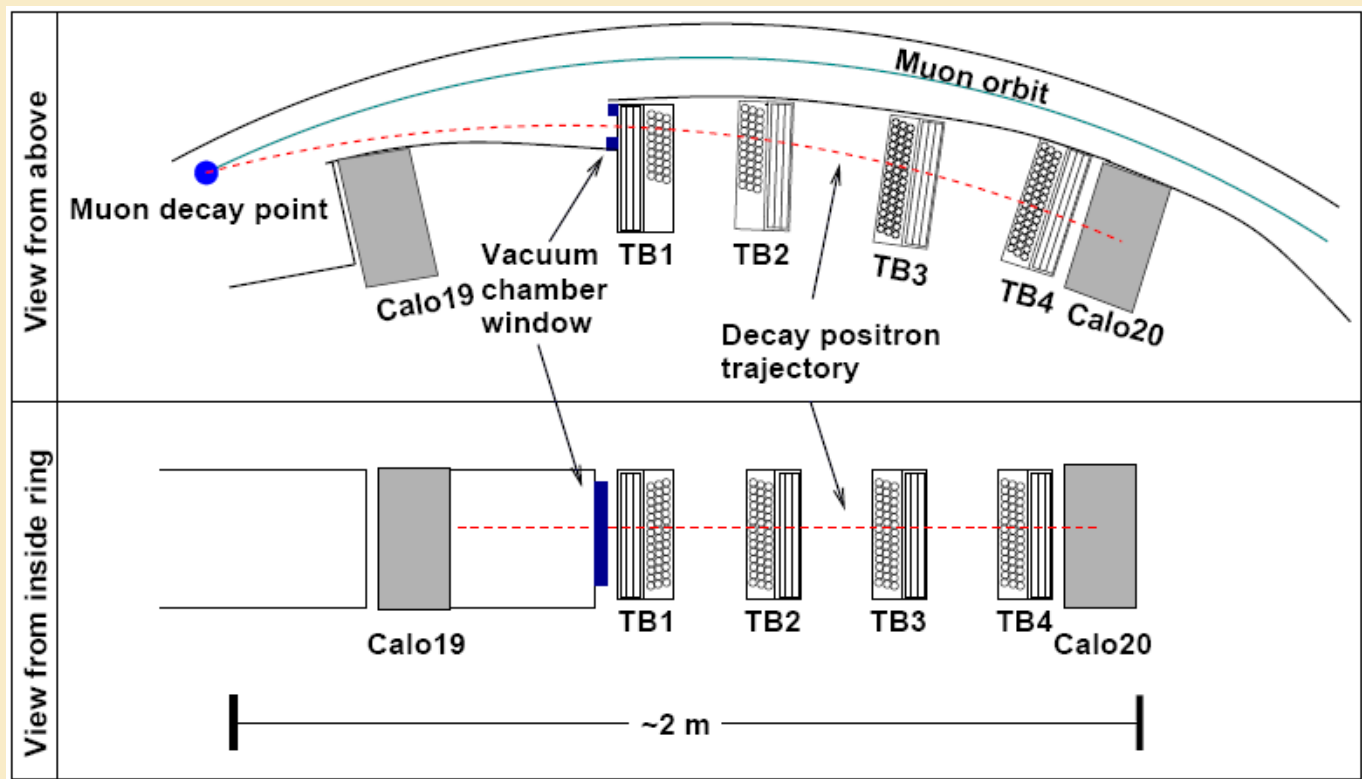


**Ultra-fast PMTs or
SiPM's?**

Ultrafast PMTs are RS 9800

Tracking Traceback detectors

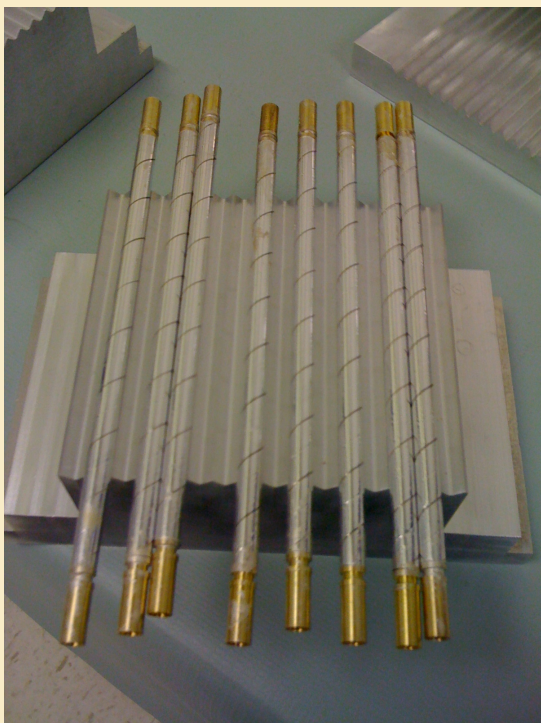
Important for pitch systematic and Muon EDM



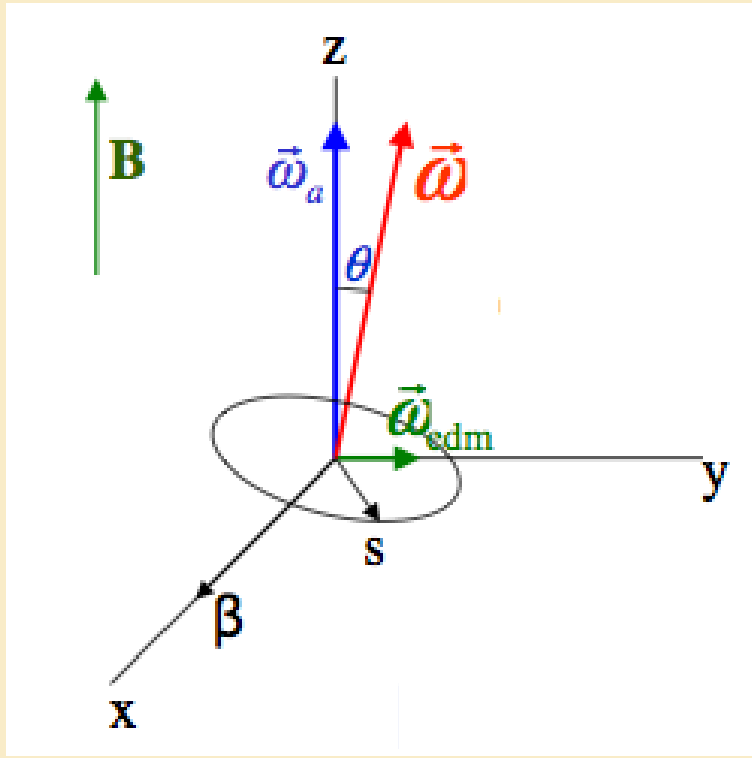
For new experiment, place straws within the vacuum



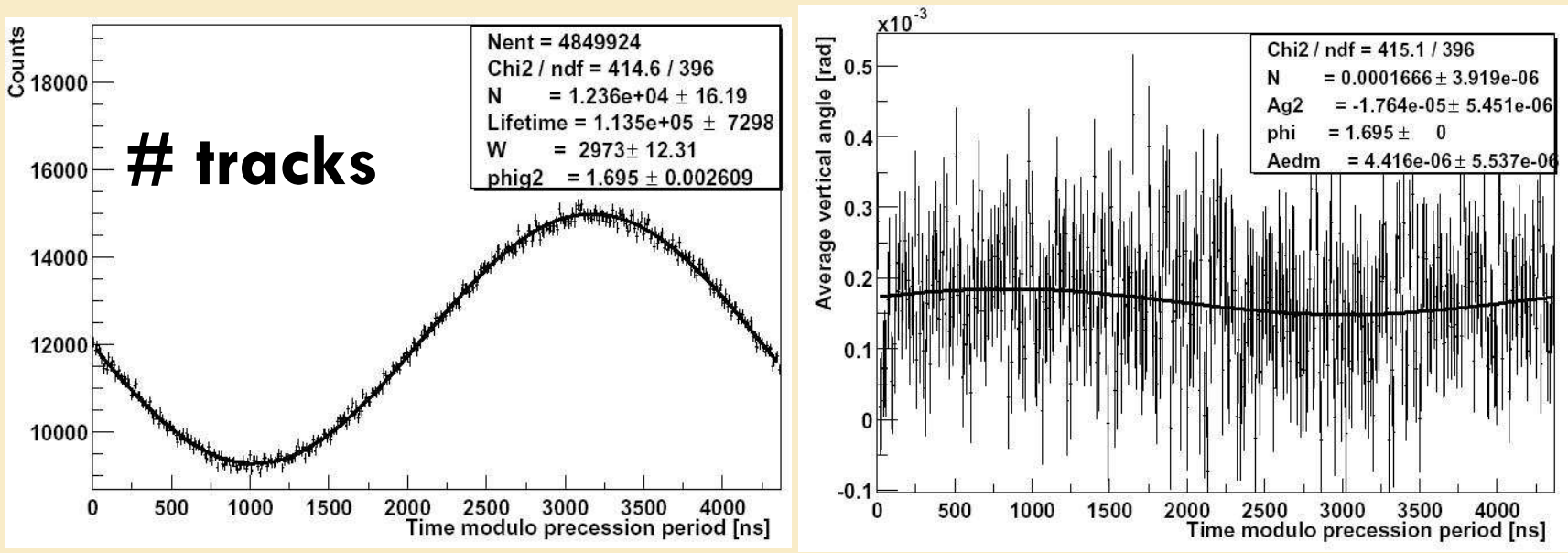
Test stand from CKM



Muon EDM



**Precession plane tilted,
vertical out of phase
oscillation of ω_a**



Current best limit from E821

$$|d_\mu| < 1.8 \times 10^{-19} \text{ e cm (95\% C.L.)}$$

**Expect 10-30x better
in new experiment**

If EDM exists – then CP violation

Improving ω_p

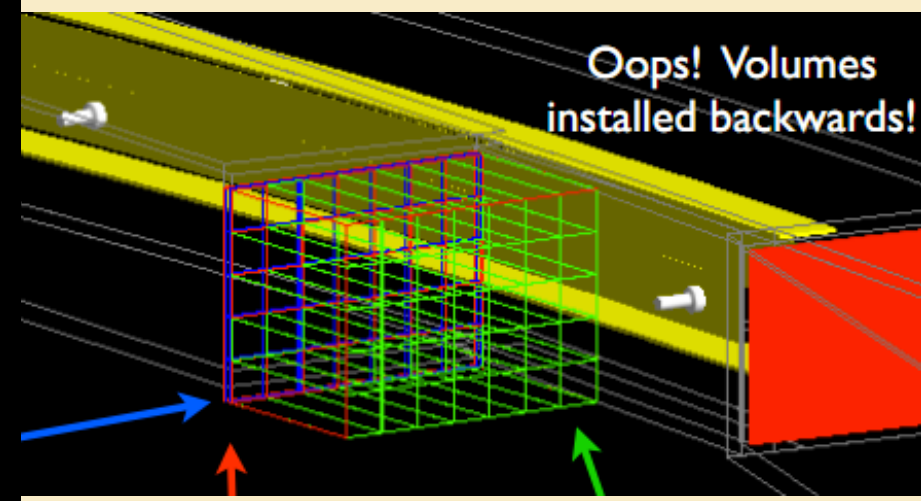
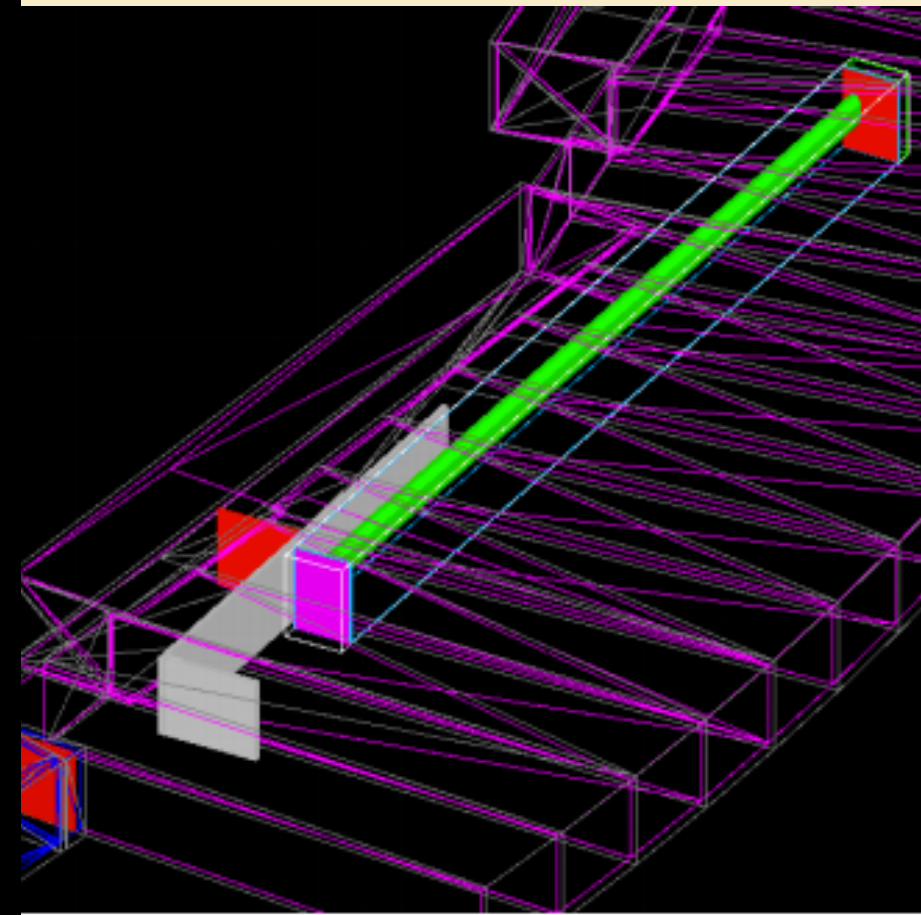
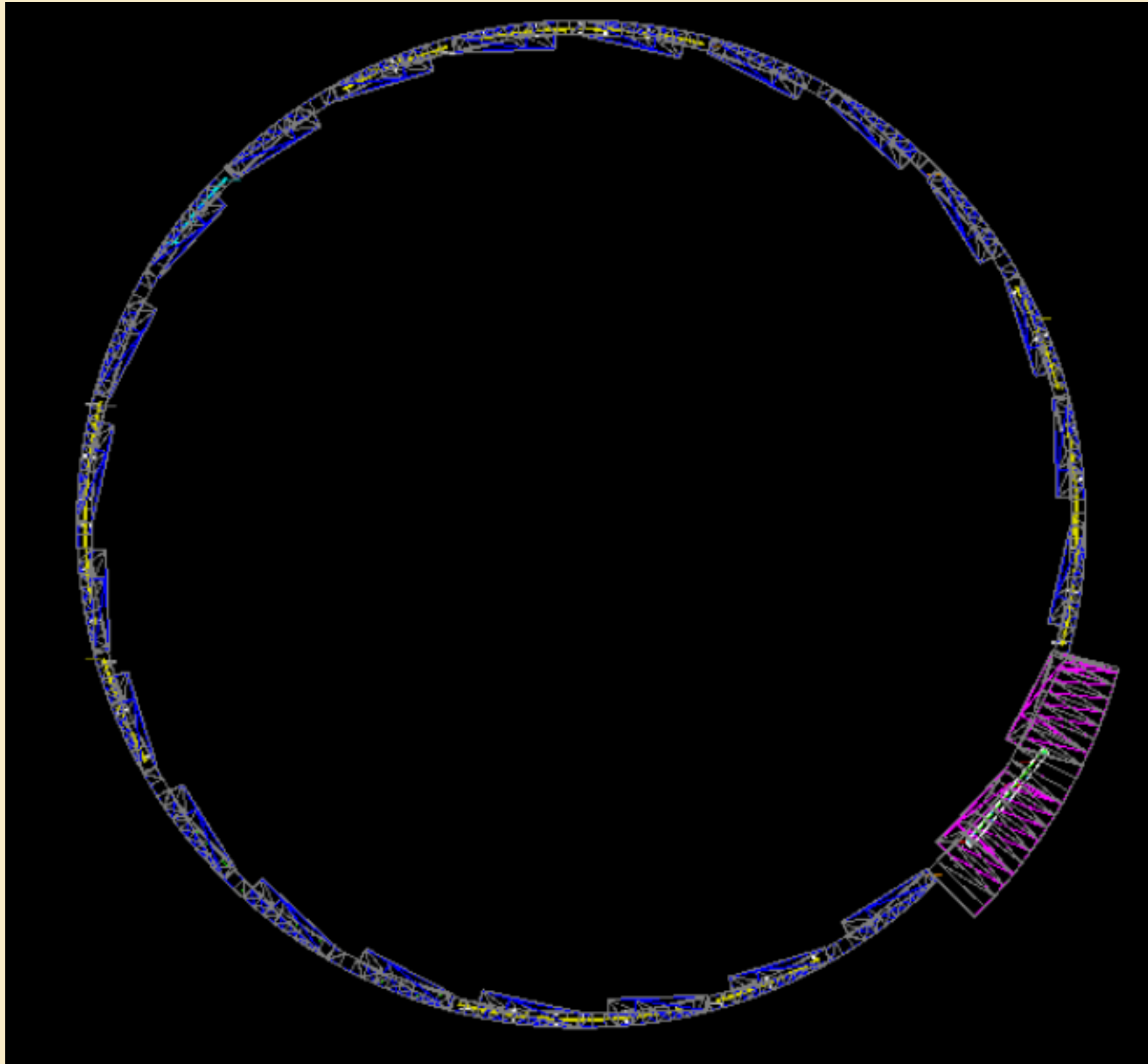
Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

To get to 0.07 ppm, more probes, mapping, shimming, temp control

More NMR probes
Will need 0.1 ppm uniformity (was 1 ppm uniformity in E821)

Geant4 Simulations

Injection to detection simulation

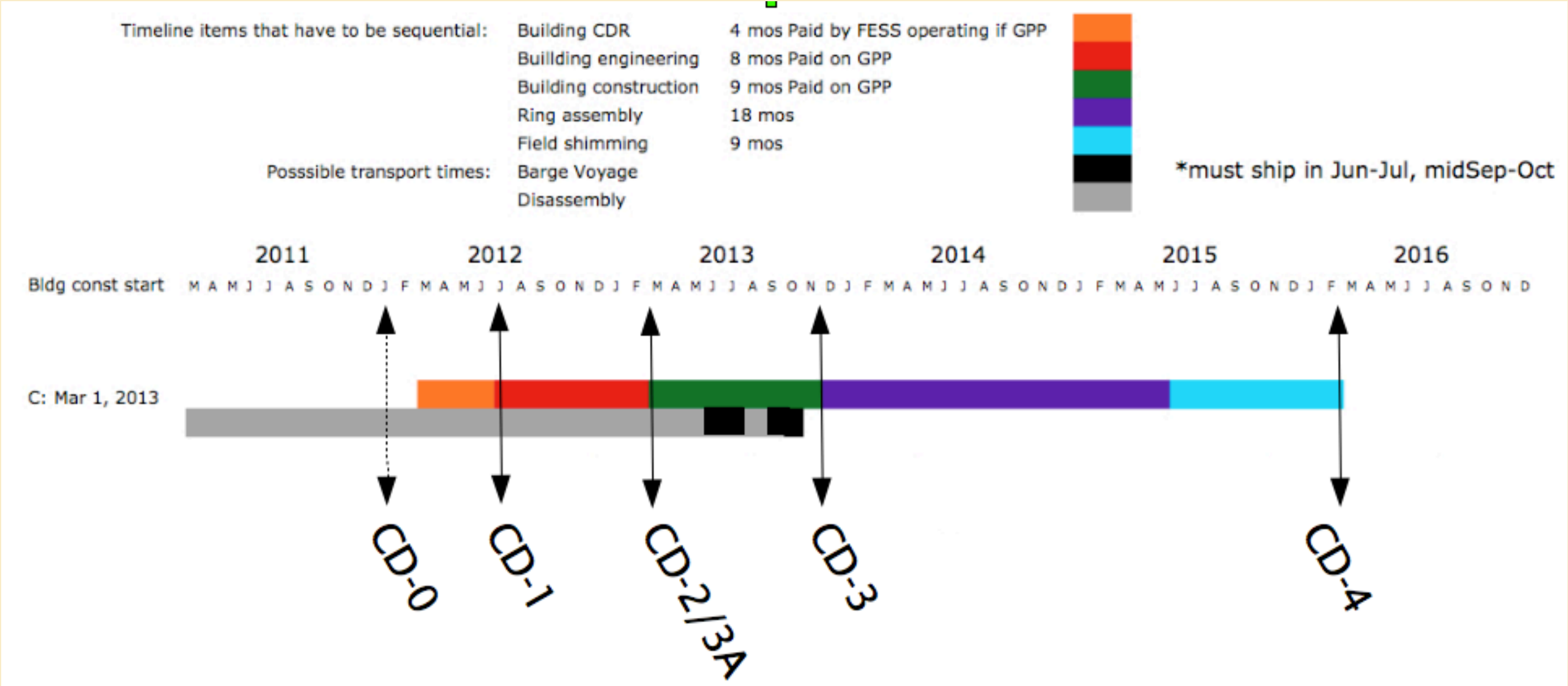


Status and timeline

Granted Fermilab Stage 1 approval (1/11)

CD-0 in early 2012

CD-1 in summer 2012, writing CDR

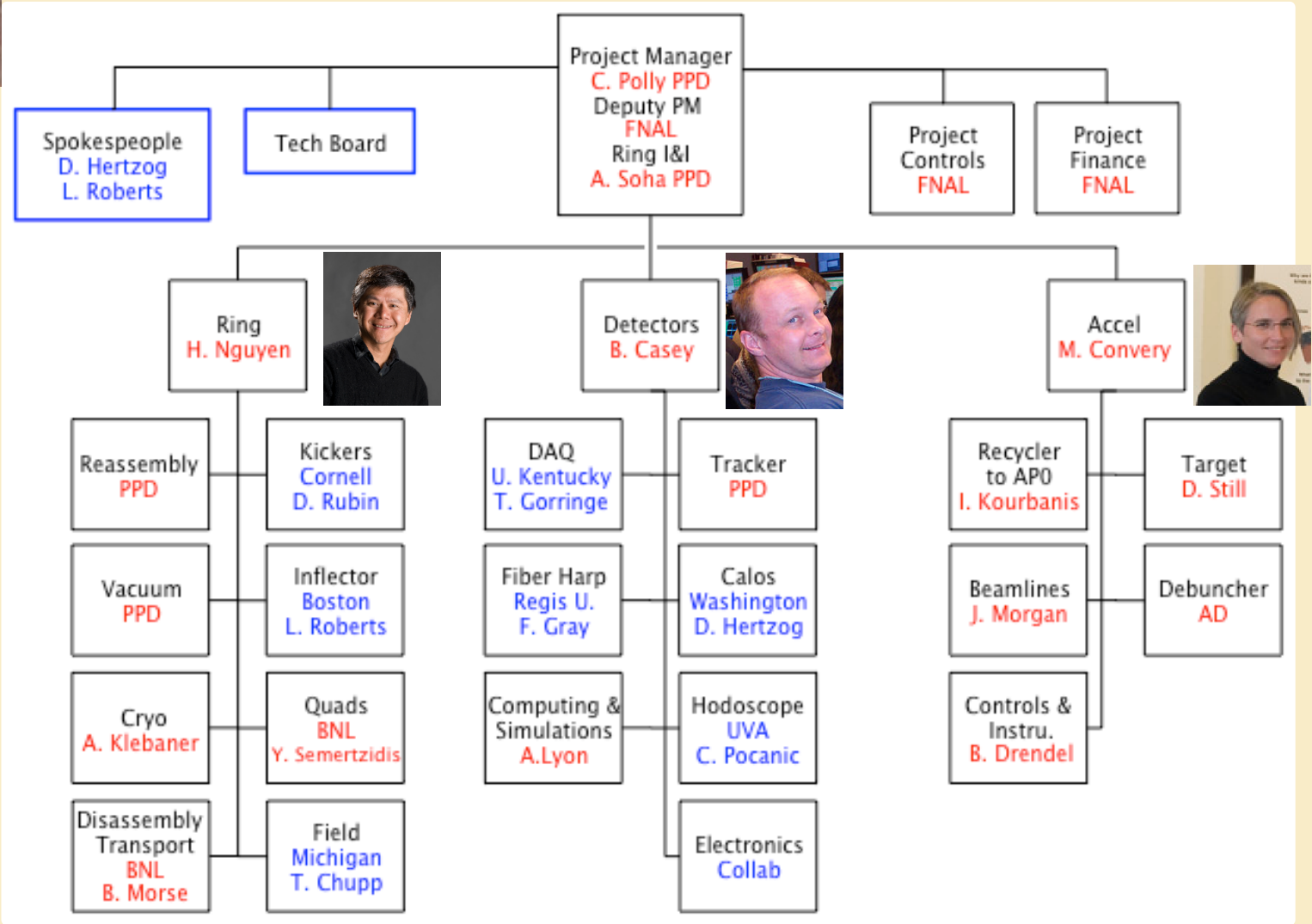


E989 Collaboration and Project

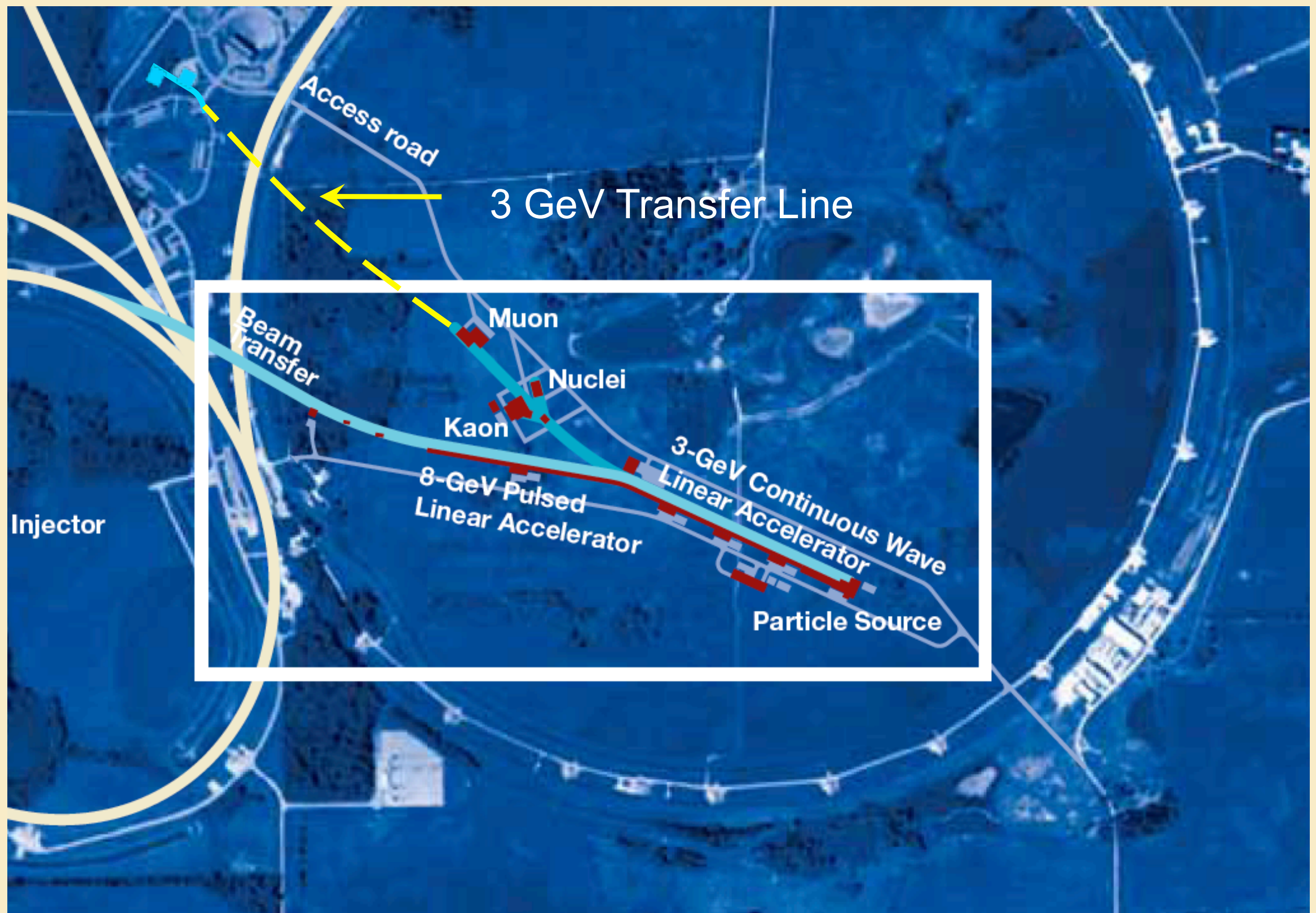


> 70 members
22 institutions

Chris Polly - Project manager



Future: Possible scenario with Project X



Summary

Muons are an excellent laboratory for fundamental physics with a long storied history

$g-2$ is extremely sensitive to minute high order SM effects and new physics

Nature is kind to these experiments with many tricks we can exploit

The 3σ discrepancy begs for further investigation

The Fermilab experiment is probably taking the magic momentum method to the limit

Future prospects are bright with $g-2$ /EDM experiments at JPARC and Fermilab/Project-X

Acknowledgements

Thanks to these papers and web sites from whom I “borrowed” images

Wikipedia

<http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html>

Chris Polly's thesis

CERN image archives

**Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110,
[arXiv:0902.3360v1](#)**

Hertzog & Morse, Annu. Rev. Nucl. Part. Sci. 2004. 54:141–74

E989 Proposal document

Various talks by Chris Polly, Dave Hertzog, Brendan Casey, Mary Convery

BACKUP SLIDES

BACKUP SLIDES

BACKUP SLIDES

Who am i?

1993 – 1997: Maryland, DØ Run 1, *Squarks+Gluinos Jets + MET*

1997 – 2002: Rochester, CLEO, $b \rightarrow s\gamma$

2002 – Fermilab/SCD, DØ Run 2, *Dibosons*

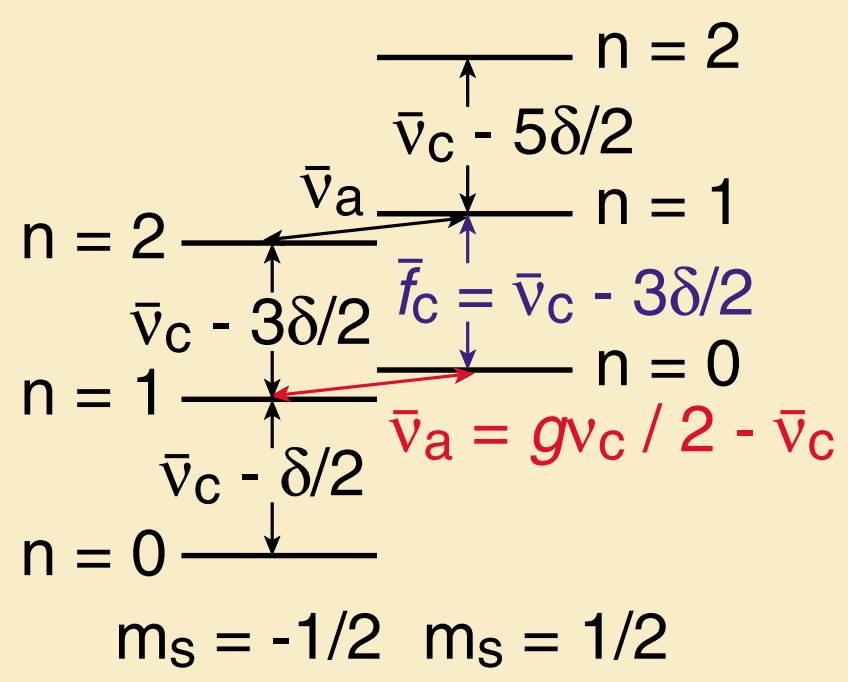
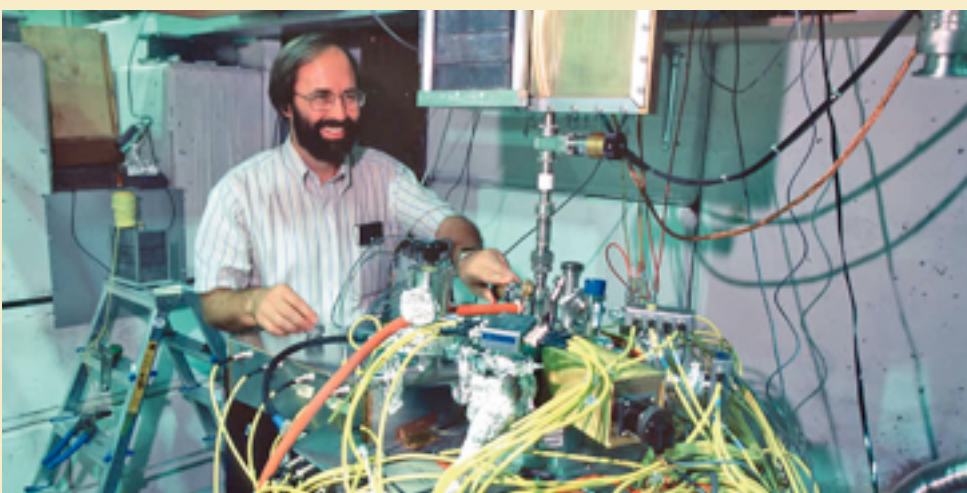
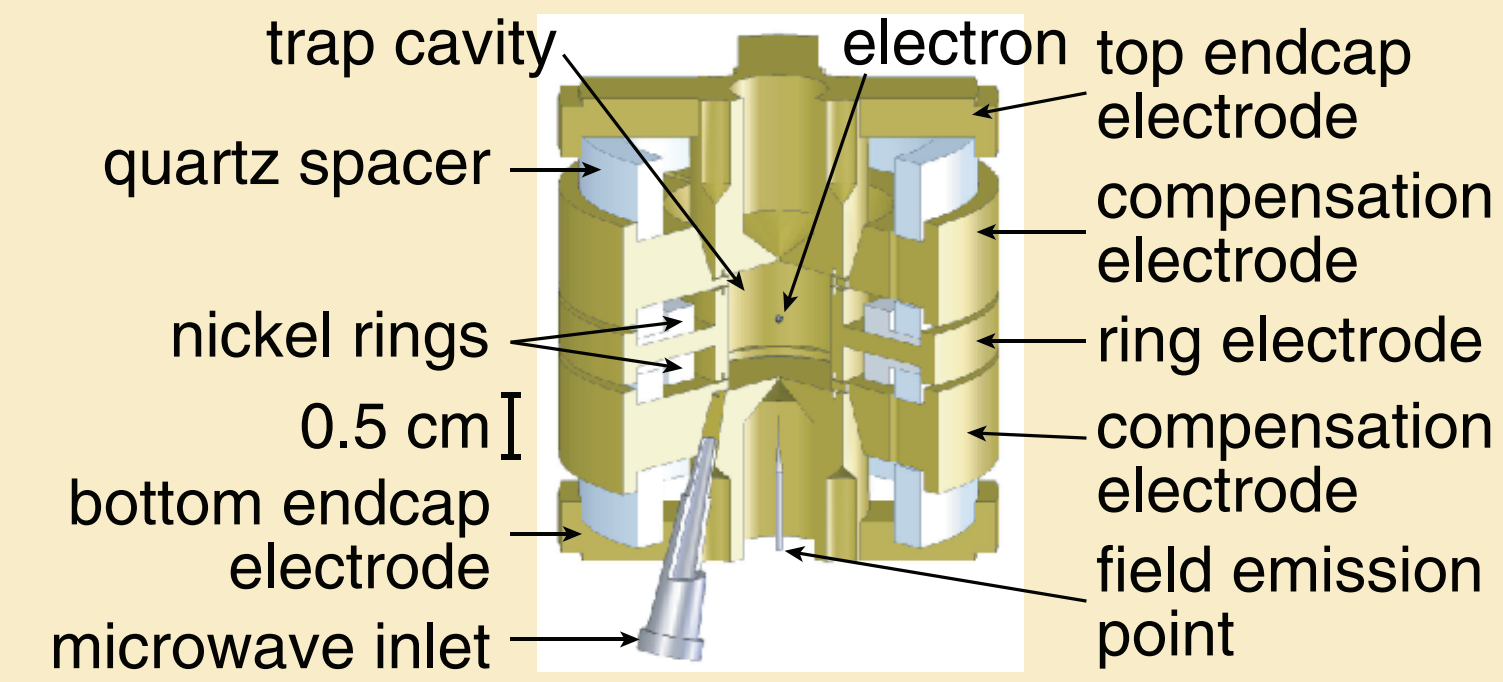
2005 – “SAM” Project Manager

2006 – Group leader of Data Handling experts

2011 – g-2 Computing and Simulations L3 manager

Currently, a_e is known to sub-ppt

Gabrielse (2006 & 2008):
Previous result was 20 years prior



- Single electron trapped for months**
- Quantum nondemolition measurement**
- e orbits horizontally in B field at 150 GHz**
- Oscillates in z at 200 MHz with electric quadrupole**
- Observe quantum jump spectroscopy**

$$a_e = 0.00115965218073(28)$$

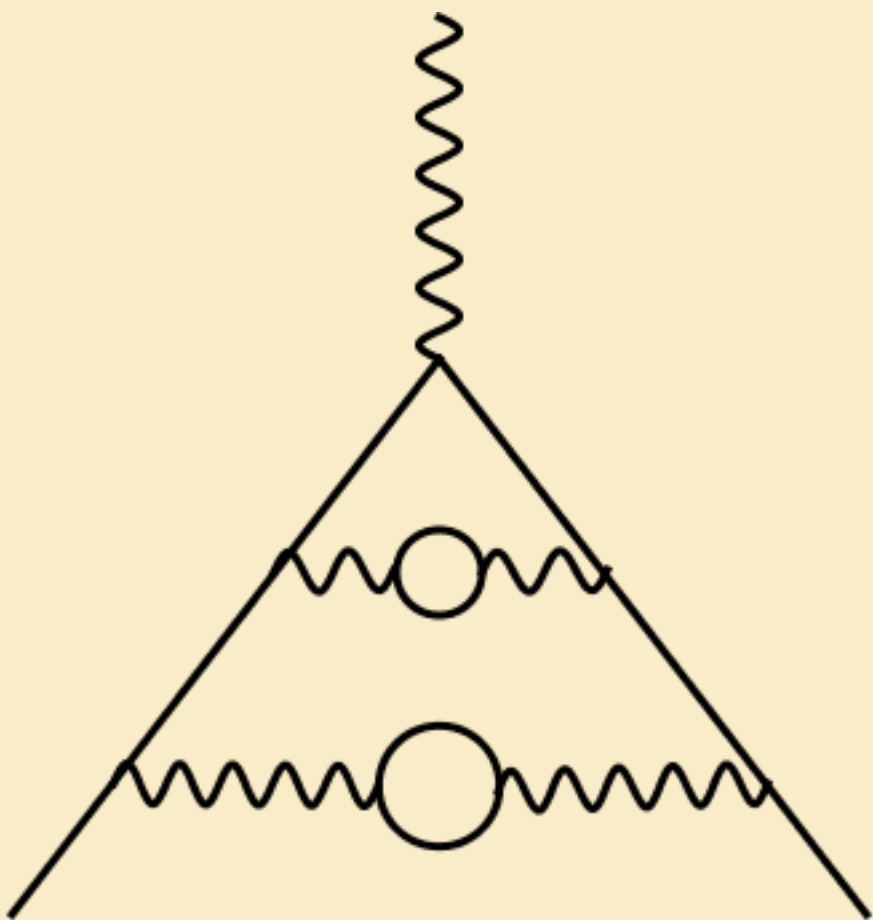
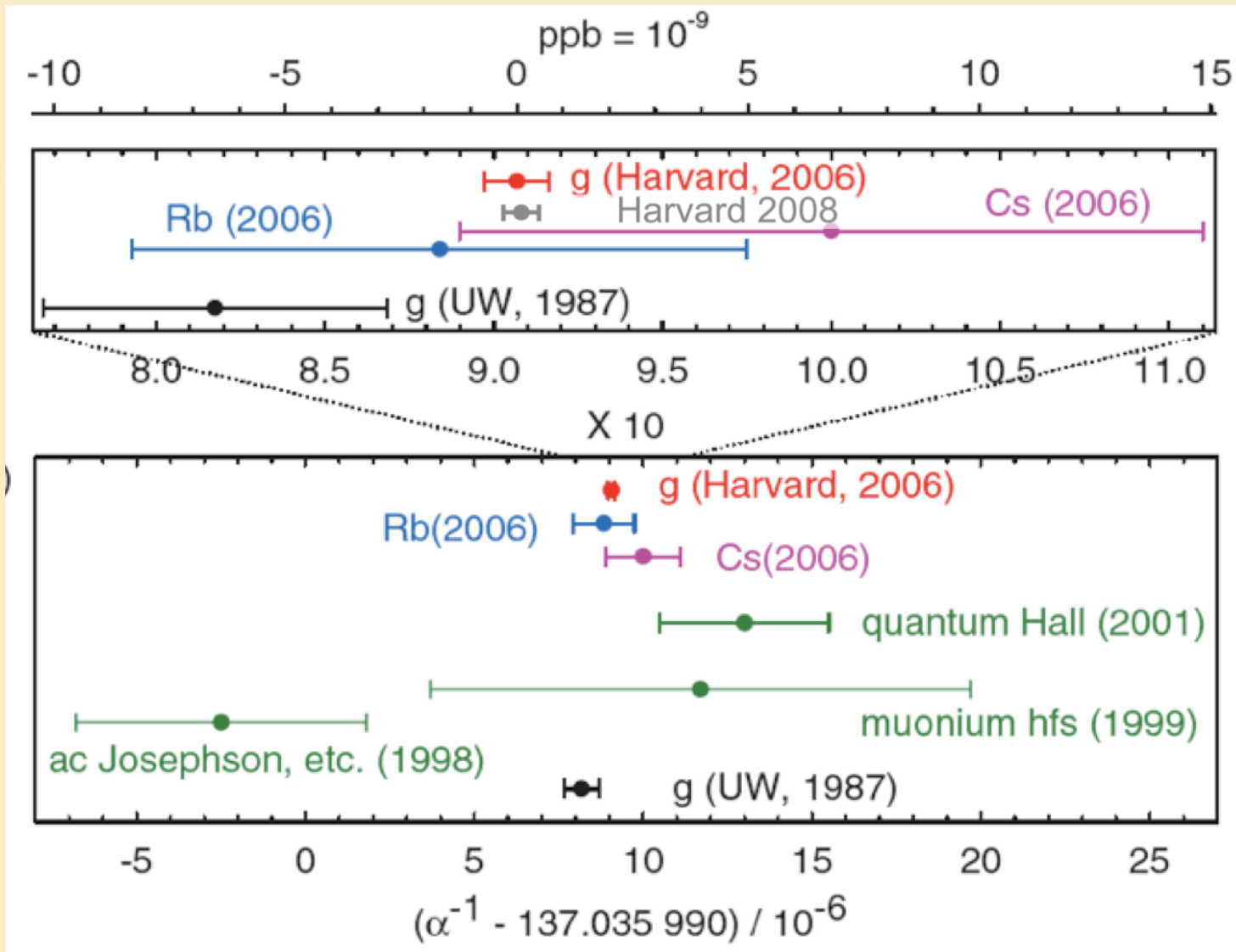
Hanneke et al., PRL100 (2008) 120801

The most accurate value of alpha is obtained

$$g/2 = 1 + C_2 \left(\frac{\alpha}{\pi}\right) + C_4 \left(\frac{\alpha}{\pi}\right)^2 + C_6 \left(\frac{\alpha}{\pi}\right)^3 + C_8 \left(\frac{\alpha}{\pi}\right)^4 + C_{10} \left(\frac{\alpha}{\pi}\right)^5 + \dots + \alpha_{\text{hadronic}} + \alpha_{\text{weak}}$$

$$\alpha^{-1} = 137.035\,999\,084\,(33_{\text{exp}})(39_{\text{th}})$$

Compare to other independent extractions

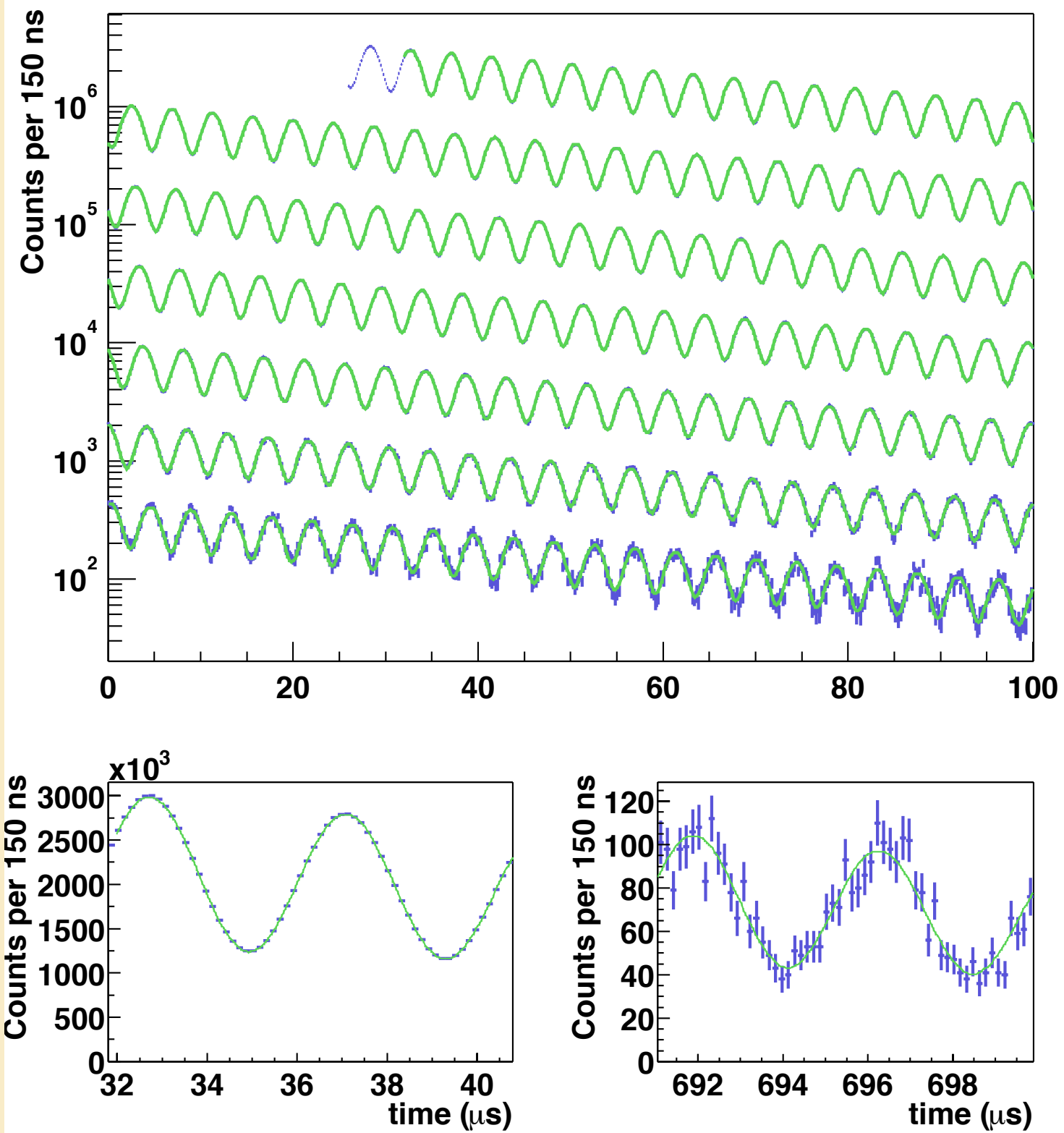


Are we done?
No, lots more
to this story...

Differences between BNL and 3rd CERN

Quantity	E821	CERN
Magnet	Superconducting	Room Temperature
Yoke Construction	Monolithic Yoke	40 Separate Magnets
Magnetic Field	1.45 T	1.47 T
Magnet Gap	180 mm	140 mm
Stored Energy	6 MJ	
Field mapped in situ?	yes	no
Central Orbit Radius	7112 mm	7000 mm
Averaged Field Uniformity	± 1 ppm	± 10 ppm
Muon Storage Region	90 mm Diameter Circle	120×80 mm ² Rectangle
Injected Beam	Muon	Pion
Inflector	Static Superconducting	Pulsed Coaxial Line
Kicker	Pulsed Magnetic	$\pi \rightarrow \mu \nu_\mu$ decay
Kicker Efficiency	$\sim 4\%$	125 ppm
Muons stored/fill	10^4	350
Ring Symmetry	Four-fold	Two-fold
$\sqrt{\beta_{\text{max}}/\beta_{\text{min}}}$	1.03	1.15
Detectors	Pb-Scintillating Fiber	Pb-Scintillator “Sandwich”
Electronics	Waveform Digitizers	Discriminators
Systematic Error on B-field	0.17 ppm	1.5 ppm
Systematic Error on ω_a	0.21 ppm	Not given
Total Systematic Error	0.28 ppm	1.5 ppm
Statistical Error on ω_a	0.46 ppm	7.0 ppm
Final Total Error on a_μ	0.54 ppm	7.3 ppm

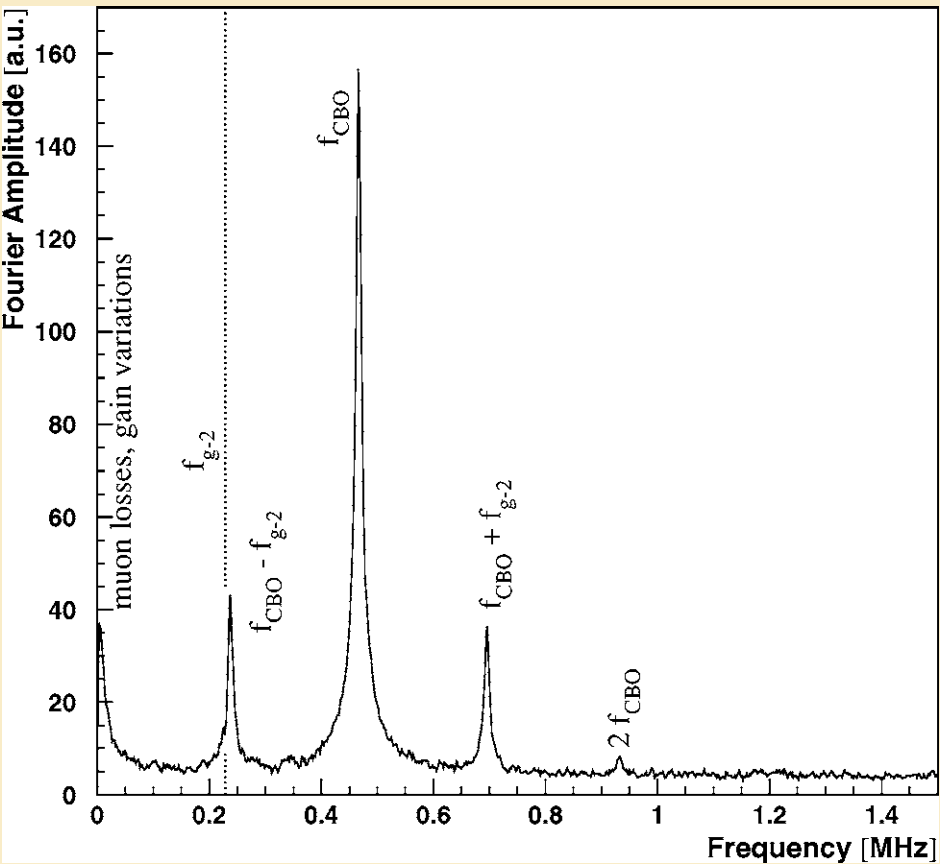
Measuring ω_a



2000 data, 4 billion decays

5 parameter fit

$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + \phi)]$$



Coherent betatron oscillation sideband near g-2 found in 2000 data. Tune changed for 2001 run to move CBO away

Frequency of CBO is 465 KHz (radial oscillation about a fixed point)

Corrections to ω_a

Not all muons exactly at magic - measure cyclotron frequency distribution, correct ω_a

Pitch correction due to vertical betatron motion - measured with traceback system (4 straw chambers to trace location of muon decay)

Fast rotation - bunch structure can remain - apply random small offset ($< \text{bin width}$) to t_0

Multiparticle pileup - allows low energy e's (with different phase) in fit, more early, less late - keep raw WFD data – subtract constructed pileup hypothesis

Lost muons - escape before decay - leads to incorrect lifetime - Hodoscopes in front of calorimeters measure rate (coincidence of 3 adjacent hodoscopes)

EDM - tilts precession plane - causes vertical oscillation of polarization - Traceback detector saw none

Lyon - New g-2 - ANL - 2012-01

86

acceptance of calorimeters is 70%

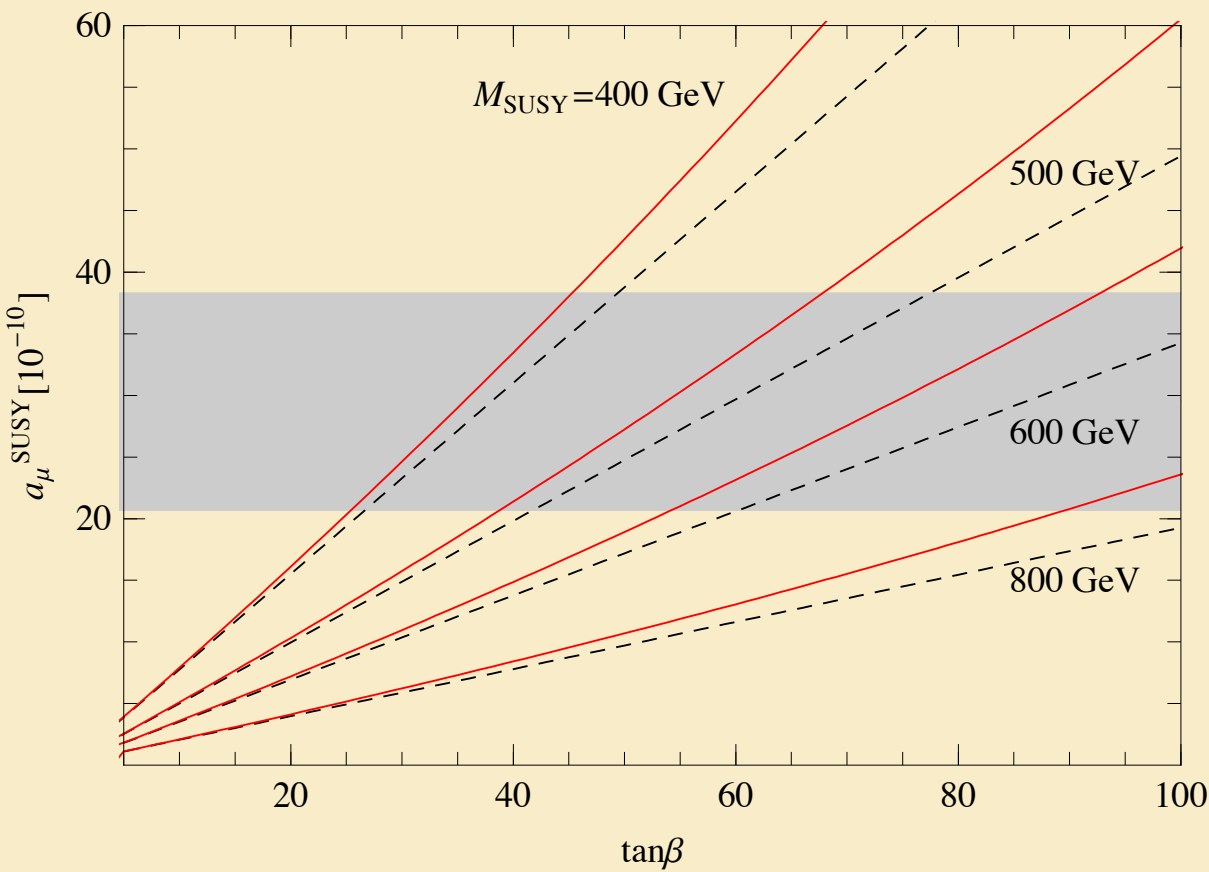
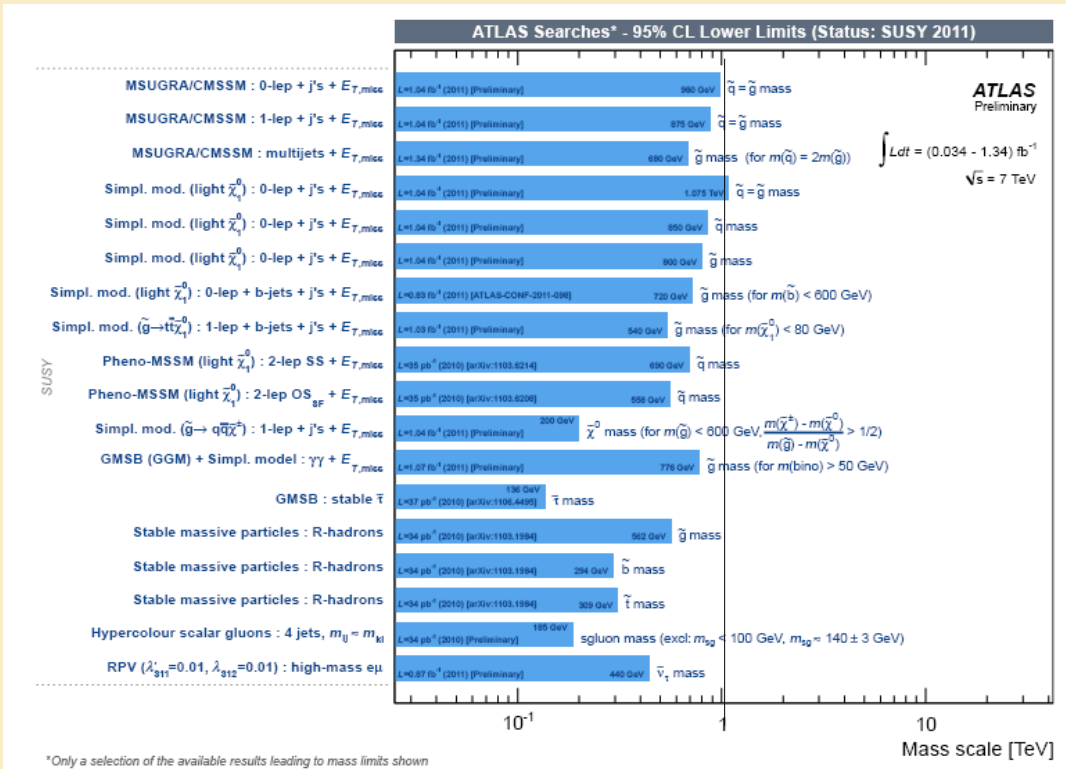
Lost muon rate was about 1% early and 0.1% late – would have incurred a 0.18 ppm shift

SUSY?

SUSY with mass scale of several 100 GeV is consistent with discrepancy

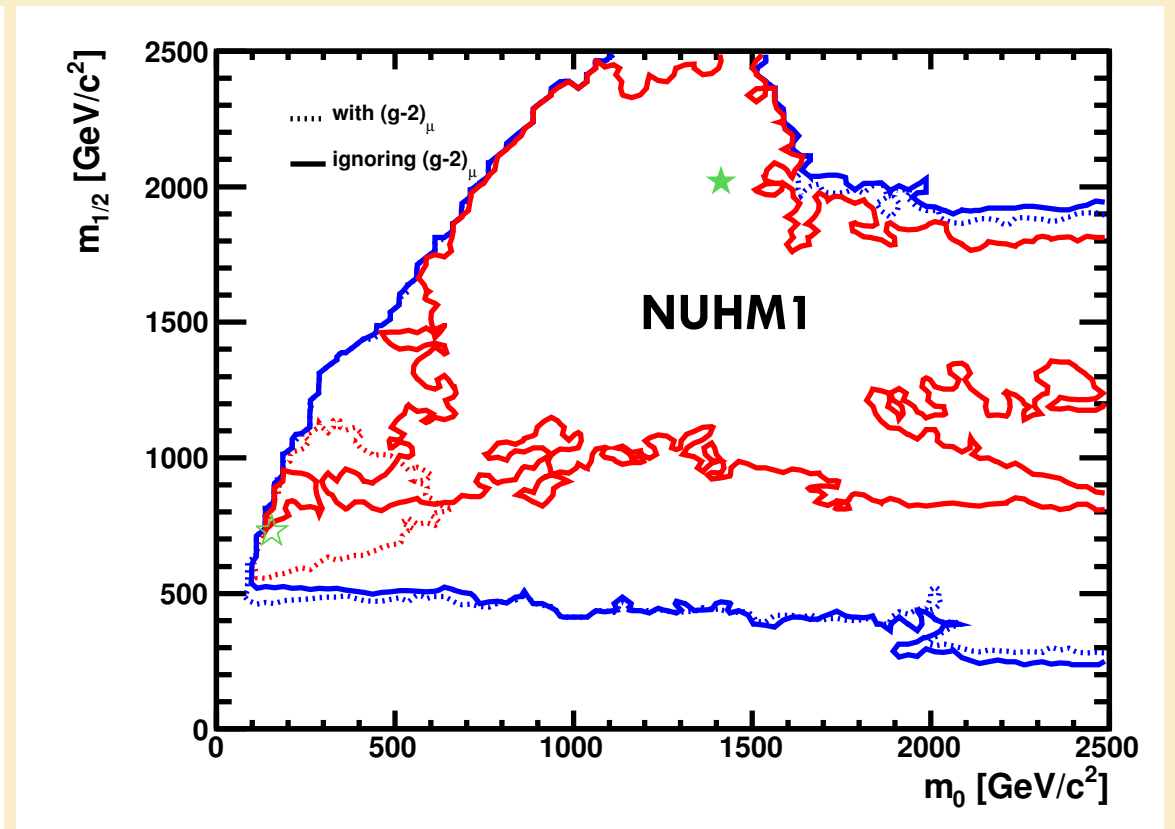
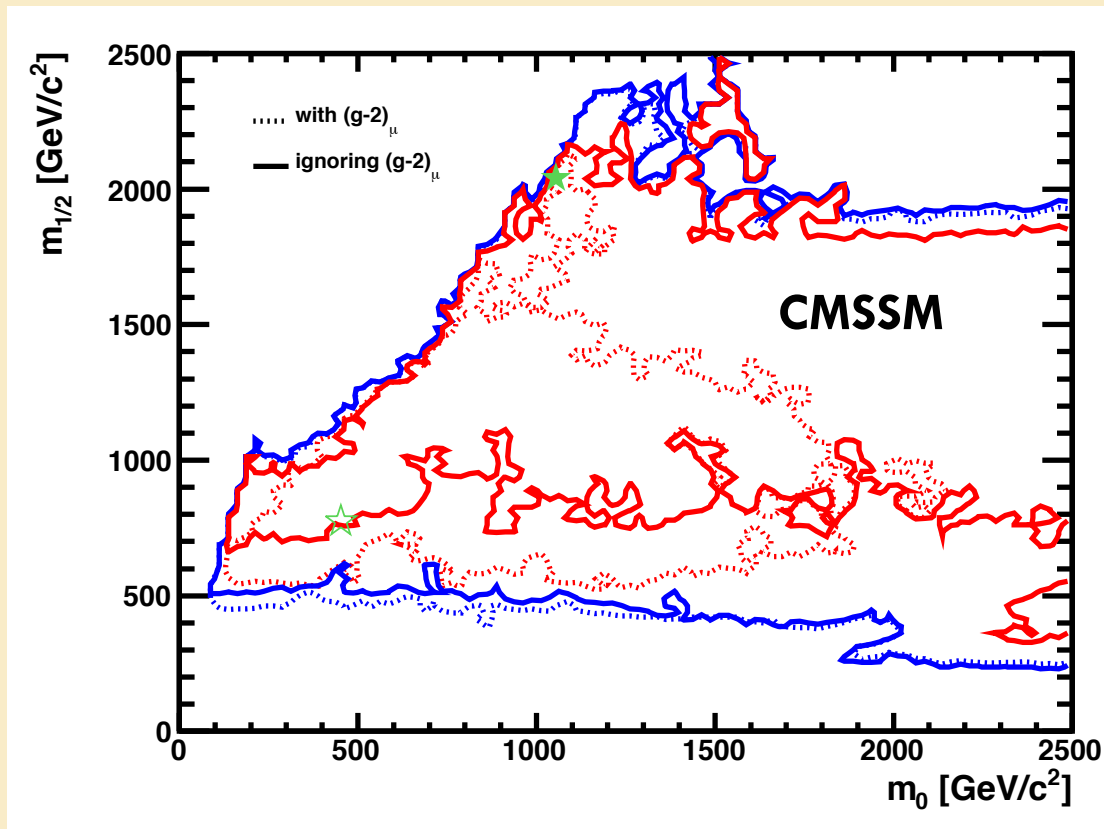
$$a_{\mu}^{\text{SUSY}} \approx 13 \times 10^{-10} \text{sign}(\mu) \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \tan \beta$$

But LHC results require large $\tan \beta$



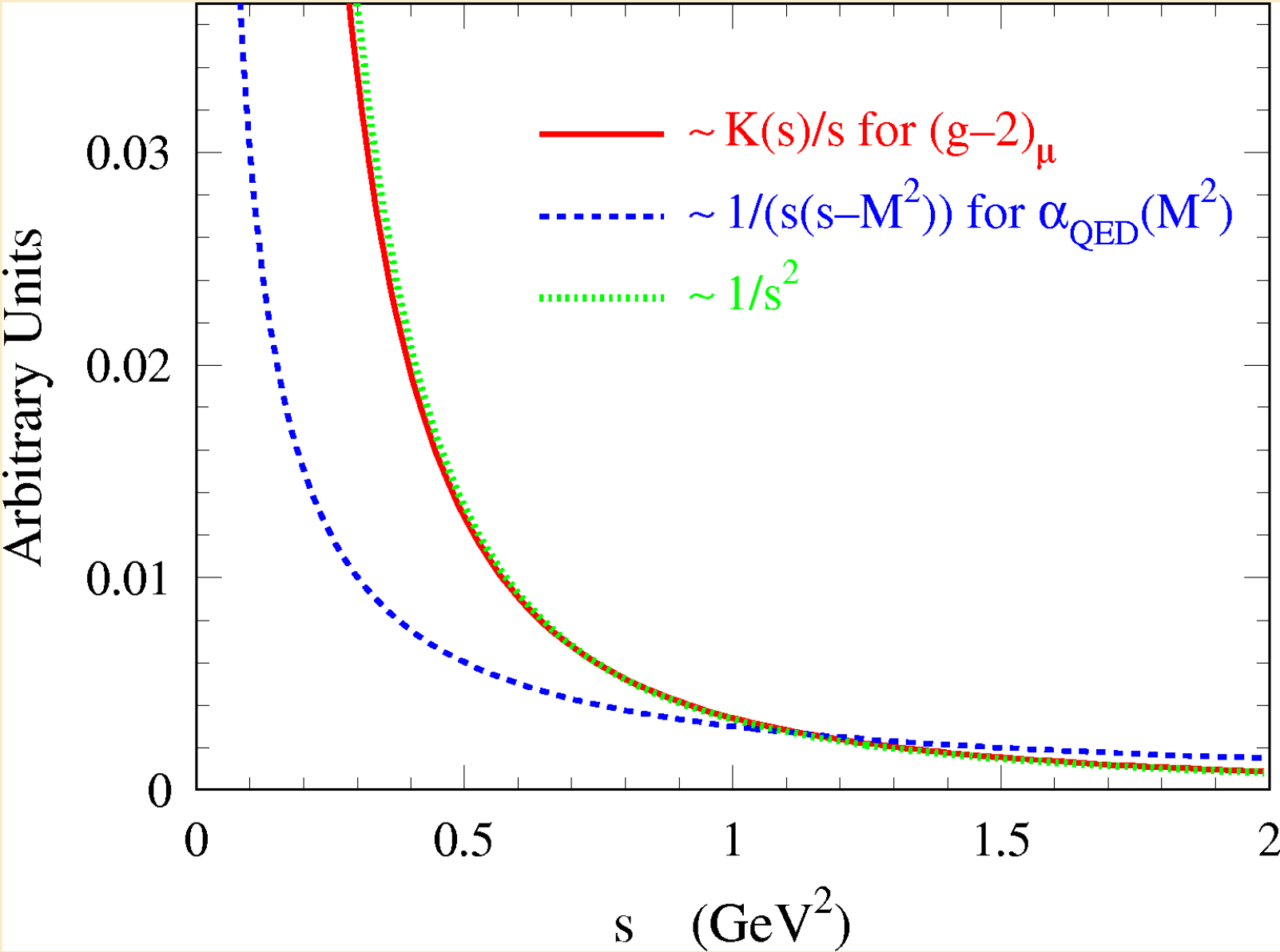
Lyon - New g-2 - ANL - 2012-01

Grey bar is BNL discrepancy
Red lines include a calculated enhancement
g-2 likes tan beta ~ 40



Global fit for best SUSY points given recent Atlas, CMS, LHCb, and other data, including g-2

HVP(LO) $K(s)$



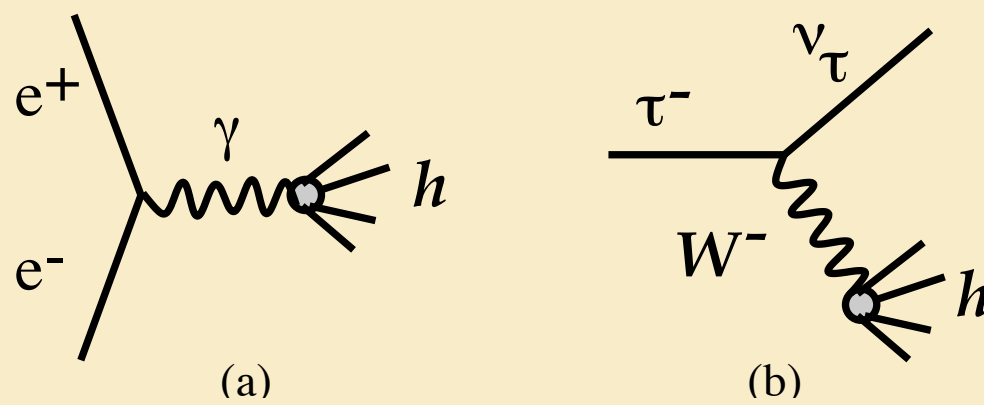
M. Davier

Taus for HVPL0

Differences between e^+e^- and tau data.

Taus need isospin corrections

But predictions of tau to pions branching fractions with CVC (Conserved Vector Current) Hypothesis disagree with experiment at few-sigma level.



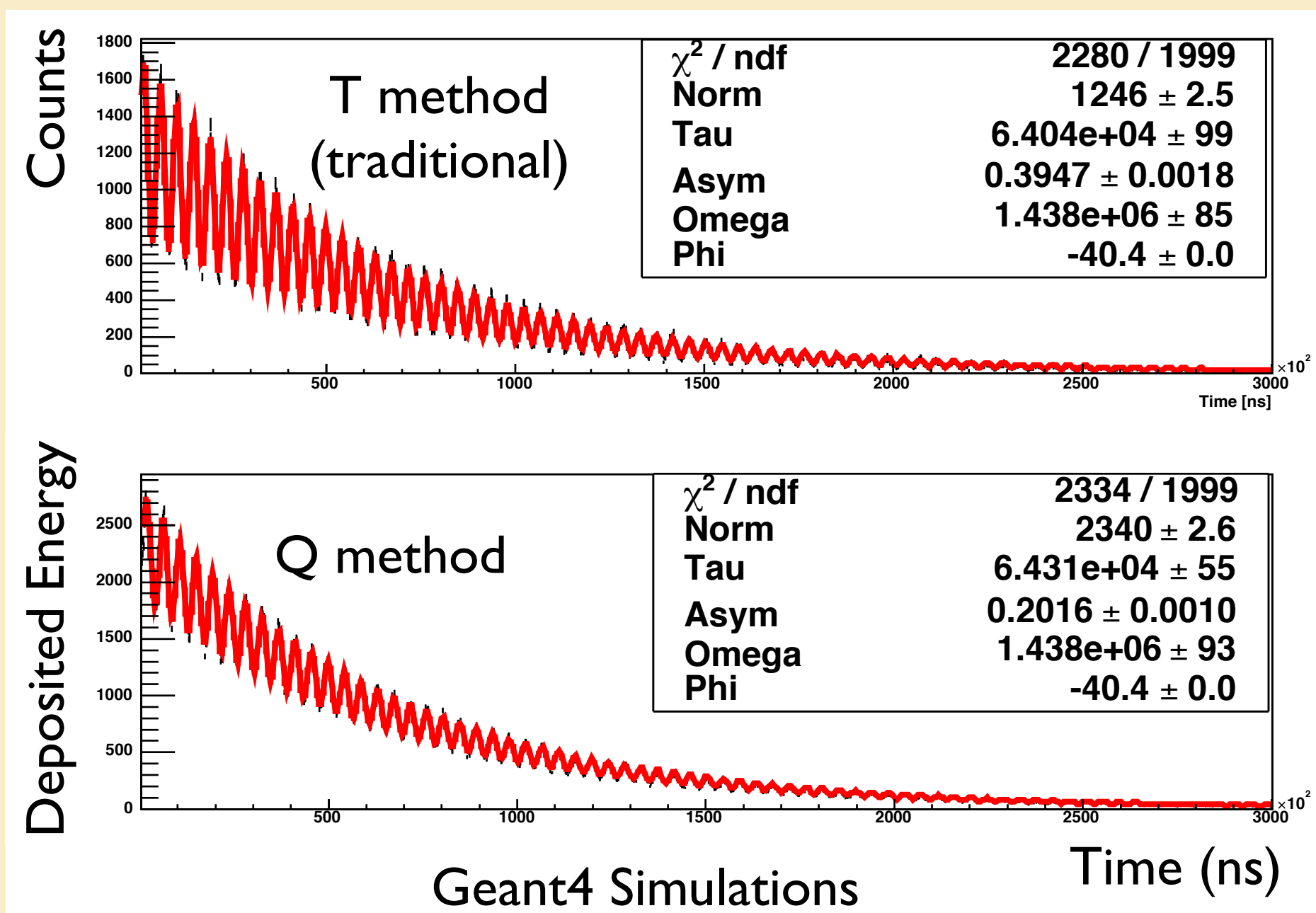
Event rate calculation

Item	Factor	Net	Note
Booster cycle - 15 Hz operation	1.33 s/cycle	0.75 Hz	1
Batches to $g-2$	6	4.51 Hz	2
Protons on target	4×10^{12} p/batch	1.80×10^{13} p/s	3
Bunches (each bunch provides 1 fill of the ring)	4 /batch	18 fills/s	4
BNL stored muons per proton	1×10^{-9} μ/p	1000 μ /Tp	5
Minimum stored μ/p improvement FNAL <i>vs.</i> BNL	6.0	6000 μ /Tp	6
Positrons with $t > 30 \mu s$ and $E > 1.8$ GeV	10 %	603 e^+ /fill	7
DAQ / Expt. production and uptime	66 %		8
Time to collect 1.8×10^{11} events (2×10^7 s/y)		1.25 years	9
Commissioning time		0.1 years	10
FNAL running years		1.35 years	11
Total Protons on Target		4×10^{20} POT	12

T's and Q's

New **Q** method:
Total cal E vs time
(no threshold)
will see wiggle
too

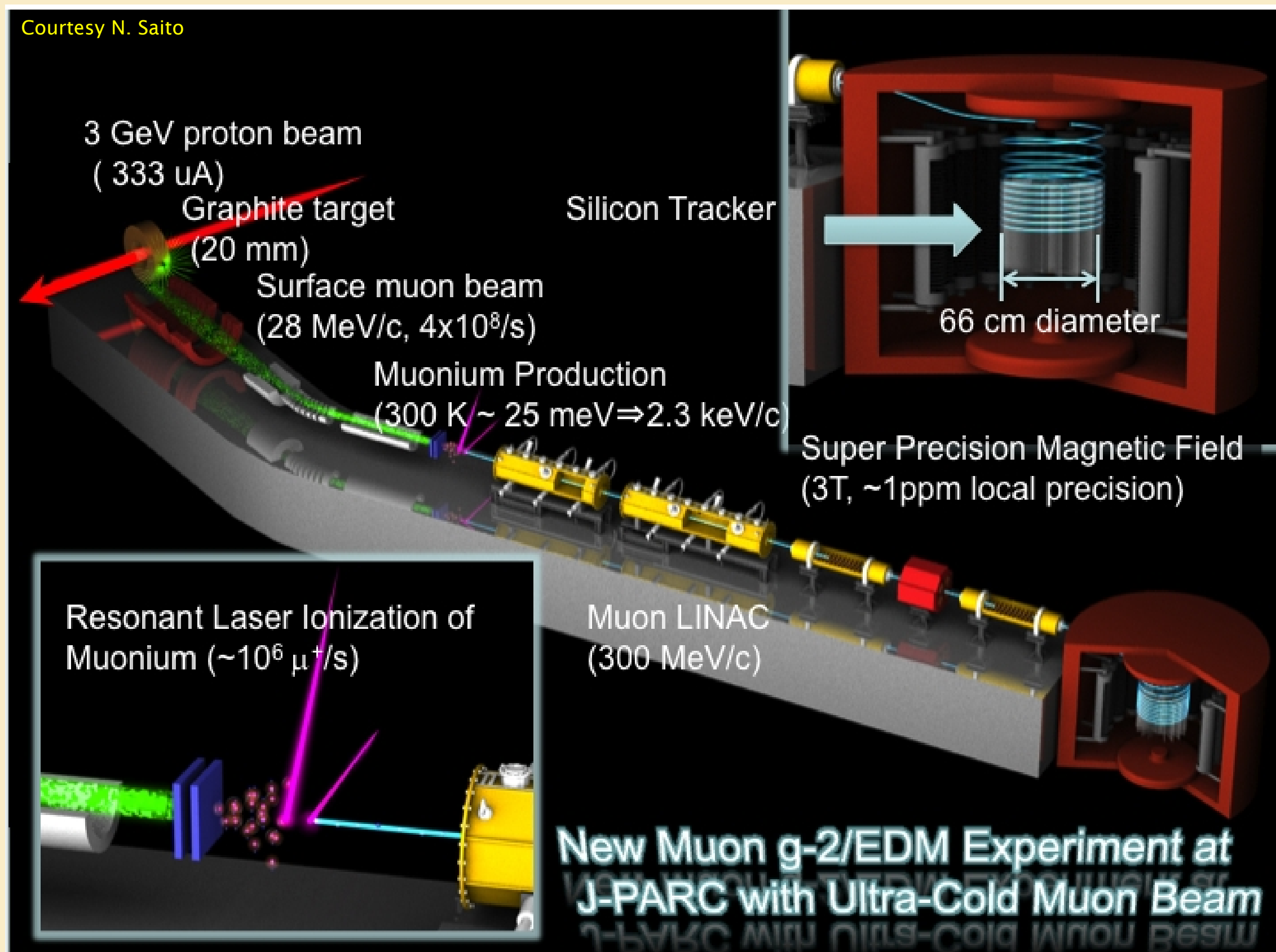
Net asymmetry is
half of T method,
but N is larger.



Statistically weaker than T method by 9%, but
no Pileup correction necessary!! Will other systematics
emerge?

Was not done in E821 because the of the WFD hardware and the significant hadronic flash
which added a slowly decaying baseline for many detectors in first half of the ring

g-2 at JPARC



Give up on magic momentum – use ultra cold muon source (<10 cm of spread in over 10 km of travel) and MRI magnet.
Same

Have to contend with higher rate in smaller device

$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A \cos(\omega_a t + \phi)]$$

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ^+ decays	5.0E9	1.8E11	1.5E12
# of detected μ^- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

⇒
$$\sigma_\omega = \frac{\sqrt{2}}{A \gamma \tau_\mu \sqrt{N}}$$

Lower γ means higher statistics required

Also need to repolarize muon source or compensate lower A

N. Saito NuFact 2011

Highly granular Si tracker, Belle II DSSD under evaluation

